Acoustic Response and Detection of Marine Mammals Using an Advanced Digital Acoustic Recording Tag

SERDP FINAL TECHNICAL REPORT

Contract No.: DACA72-01-C-0011
Project No.: SI-1188

Performing Organization:
Woods Hole Oceanographic Institution
Biology Department
Woods Hole, MA 02543

Lead Principal Investigator:
Peter L. Tyack

13 March 2007
Revision No.: 3

A *Ziphius cavirostris* in the Canary Islands. Photo Credit: Victor Gonzalez, University of La Laguna. Fieldwork was supported by University of La Laguna and Governments of El Hierro and the Canary Islands. Research was conducted under US NMFS permits no. 981-1578-02 and 981-1707-00 and a permit from the government of the Canary Islands.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
13 March 2007	Final Technical	1/24/2001 - 6/30/2006

4. TITLE AND SUBTITLE

Acoustic Response and Detection of Marine Mammals Using an Advanced Digital Acoustic Recording Tag

5a. CONTRACT NUMBER DACA72-01-C-0011

5b. GRANT NUMBER N/A

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Peter L. Tyack

5d. PROJECT NUMBER SI-1188

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Woods Hole Oceanographic Institution
Woods Hole, MA 02543

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

SERDP Support Office
HydroGeoLogic, Inc
1155 Herndon Parkway, Suite 900
Herndon, VA 20170

10. SPONSOR/MONITOR'S ACRONYM(S)

SERDP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Marine mammals are protected by three Acts of Congress: the Marine Mammal Protection Act of 1972 (MMPA), the Endangered Species Act of 1973 (ESA), and the National Environmental Protection Act (NEPA) of 1969. The MMPA prohibits any person or vessel subject to the jurisdiction of the United States to take a marine mammal where "take" is defined as "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal." Most of the large whale species were placed on the U.S. Endangered Species List in 1970, which has a similar prohibition on “taking”. The Department of Defense, as a branch of the Federal government, is required under NEPA to evaluate the potential environmental impacts of major actions or activities.

The need for environmental compliance regarding marine mammals and anthropogenic sound creates a need to develop methods to assess the impacts on marine mammal populations. SERDP, the Office of Naval Research, and the environmental readiness branch

15. SUBJECT TERMS

marine mammals, passive acoustic monitoring, effects of noise, anthropogenic sound, electronic tags, behavior, beaked whales

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclass	Unclass	Unclass	UL		Dr. Peter L. Tyack
					19b. TELEPHONE NUMBER *(Include area code)* 508-289-2818

Reset

Table of Contents

List of Acronyms

ATOC	Acoustic Thermometry of Ocean Climate
AUTEC	Atlantic Undersea Test and Evaluation Center
AUV	Autonomous Underwater Vehicle
BMMS	Bahamas Marine Mammal Survey
CD	Compact Disc
CEE	Controlled Exposure Experiment
CNC	Computer Numerical Control
CNO N45	Chief of Naval Operations Environmental Protection, Safety and Occupational Health Division
dB	Decibel
DCS	Decompression Sickness
DFD	Deep Foraging Dive
DI	Directionality Index
DoD	Department of Defense
DT	Detection Threshold
DTAG	Digital Acoustic Recording Tag (V1: version 1 & V2: version 2)
EKG	Electrocardiogram
ESA	Endangered Species Act of 1973
ESWTR	East Coast Shallow Water Test Range
FFT	Fast Fourier Transform
GB	Gigabyte
GPS	Global Positioning System
Hz	Hertz
IACUC	Institutional Animal Care and Use Committee
ICI	Inter-click-Interval
IR	Infrared
kHz	kilohertz
kg	kilogram
km	kilometer
lb	pound
m	meter
MB	Megabyte
Mbit/s	megabit-per-second
Md	*Mesoplodon densirostris*, Blainville's beaked whale
MMPA	Marine Mammal Protection Act of 1972
msec	millisecond
NATO	North Atlantic Treaty Organization
NC	North Carolina
NEPA	National Environmental Protection Act
NL	Noise Level
NMFS	National Marine Fisheries Service
NOPP	National Oceanographic Partnership Program
NRC	National Research Council
NURC	NATO Undersea Research Centre

NUWC	Naval Undersea Warfare Center
NUWC M3R	Naval Undersea Warfare Center Marine Mammal Monitoring on Range
ONR	Office of Naval Research
Pa	Pascal
PC	Personal Computer
PDA	Personal Digital Assistant
re	in reference to
RHIB	Rigid Hull Inflatable Boat
RL	Received Level
RMS	Root of the Mean Squared
SAIC	Science Applications International Corporation
SC	South Carolina
sec	second
SERDP	Strategic Environmental Research and Development Program
SL	Source Level
SON	Statement of Need
SPAWAR	Space and Naval Warfare Systems Command
SST	Sea Surface Temperature
SURTASS LFA	Surveillance Towed Array Sensor System Low Frequency Active
TL	Transmission Loss
ULL	Universidad de La Laguna
UNCW	University of North Carolina, Wilmington
US	United States
VHF	Very High Frequency
WHOI	Woods Hole Oceanographic Institution
Z	Zulu or Coordinated Universal Time (UTC)
Zc	*Ziphius cavirostris*, Cuvier's beaked whale
μPa	microPascal
μsec	microsecond

List of Figures

List of Tables

Acknowledgements

We would like to thank the Strategic Environmental Research and Development Program (SERDP) for the financial assistance which enabled us to undertake this project. Appreciation for technical assistance is extended to Mr. Bradley Smith, Executive Director and Drs. Robert Holst and John Hall, past and present Sustainable Infrastructure Program Managers, respectively, and to the Hydrogeologic, Inc., staff for their administrative assistance. We would like to thank Alessandro Bocconcelli, the Field team in El Hierro and the Field team in Liguria. Fieldwork support was provided by Universidad de La Laguna (ULL), BluWest, NATO Undersea Research Center (NURC), and Governments of El Hierro and the Canary Islands. Some of Peter Madsen's work was supported by a Steno Fellowship from the University of Aarhus in Denmark. Thanks to Mike Carron and Angela D'Amico of NURC for leading the Sirena cruises and providing Visual Marine Mammal Sighting data logging software. Walter Zimmer from NURC collaborated with analyses and write up of click patterns of beaked whales. David Moretti and his team at the Naval Undersea Warfare Center (NUWC) in Newport RI collaborated on passive acoustic monitoring at the Atlantic Undersea Test and Evaluation Center (AUTEC) range. Thanks to range personnel for help with conducting the field work, particularly Jose Arteiro, our test program manager. Diane Claridge of the Bahamas Marine Mammal Survey (BMMS) provided expert field collaborations in the Bahamas. Kim Urian, Alessandro Bocconcelli, Laela Sayigh and Lynne Williams of the University of North Carolina at Wilmington (UNCW) conducted the Onslow Bay field work. Initial funding for tag development was provided by the Office of Naval Research (ONR). Funding for some of the field work was supplemented by the National Oceanographic Partnership Program and by the Chief of Naval Operations Environmental Protection, Safety and Occupational Health Division (CNO-N45) under a subcontract from the Science Applications International Corporation (SAIC). Research was conducted under United States (US) National Marine Fisheries Service (NMFS) permit # 981-1578-02 in 2003 and permit # 981-1707 in 2004-2006. This research was approved by the Woods Hole Oceanographic Institution (WHOI) Institutional Animal Care and Use Committee (IACUC). Reports were generated by Peter Tyack and Amanda Hansen.

1. Executive Summary

1.1 Background re need for the project

Marine mammals are protected by three Acts of Congress: the Marine Mammal Protection Act of 1972 (MMPA), the Endangered Species Act of 1973 (ESA), and the National Environmental Protection Act (NEPA) of 1969. The MMPA prohibits any person or vessel subject to the jurisdiction of the United States from taking a marine mammal where "take" is defined as "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal." Most of the large whale species were placed on the US Endangered Species List in 1970, which has a similar prohibition on "taking". The Department of Defense (DoD), as a branch of the Federal government, is required under NEPA to evaluate the potential environmental impacts of major actions or activities.

The need for environmental compliance regarding marine mammals and anthropogenic sound creates a need to develop methods to assess the impacts on marine mammal populations. Strategic Environmental Research and Development Program (SERDP), ONR, and CNO N45 have made major progress in the past decade on this issue. Major advances have been made in the detection and localization of marine mammal sounds, especially the low frequency calls of baleen whales (SERDP project CS-48). Through a series of temporary threshold shift experiments, it is now known what levels of sound may start to cause effects on hearing in dolphins and seals (Kastak and Schusterman 1998; Finneran et al. 2002; Nachtigall et al. 2003). A major research effort defined the behavioral responses of four species of baleen whales to different received levels of the Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) sonar (SERDP project CS-1069).

As the FY 2001 SERDP Statement of Need (SON) entitled Marine Mammal Monitoring (CSSON-01-03) indicates, there has been a growing need for improved techniques to monitor toothed whales and their reactions to sound. Toothed whales are more common than the baleen whales and have hearing and vocalization ranges extending to considerably higher frequencies. Several Navy ranges have broad bandwidth hydrophones that are well-suited to monitoring the high frequency calls of toothed whales. Methods for detection and localization of these calls are being developed by NUWC Newport and other research groups. A major goal of this project was to develop and validate methods for passive acoustic monitoring of toothed whales, especially beaked whales. These techniques offer promise for detecting the otherwise elusive beaked whales, for improving monitoring capabilities, and will also provide a means for monitoring the long term effects of sounds associated with naval activities in a fixed habitat.

1.2 Passive acoustic monitoring for toothed whales

The SON on marine mammal monitoring lists the requirement for verifying the probability of detecting marine mammals, and the probability of correct classification, using acoustic or non-visual monitoring. The probability of detecting an animal using passive acoustics is the product of two conditional probabilities: (i) the probability of vocalization, which will vary with species, gender, age, and activity, and (ii) the probability of detecting a given call. Clearly, information is needed on:

- The source level (SL) and spectral characteristics of the calls of each species.

- The probability of an animal remaining silent, and how this varies with age and sex.
- The identification and location of individual vocalizing animals that are detected using hydrophones.

The technical approach adopted to obtain data on these topics for this project involved development of a digital acoustic recording tag technology, the DTAG, which provides high-fidelity, calibrated on-animal recordings of vocalizations. The DTAG is the optimal method, and in many cases the only method, to obtain data on how often an animal vocalizes and to obtain a clean record of the vocalization with 100% certain species identification. The tag provides the precise times and waveforms of vocalizations together with the depth and orientation of the animal and a number of behavioral cues.

1.3 Impacts of defense activities on marine mammals

The second area of need listed in the SON on marine mammal monitoring was an assessment of the short and long-term impacts of defense activities on marine mammals. The methods proposed for long term assessments of impact included a census of marine mammals near the East Coast Shallow Water Test Range (ESWTR) and collaborating with NUWC on monitoring location and vocal behavior of marine mammals on the AUTEC range. The work near ESWTR sampled one small resident population of spotted dolphins, and a large migratory population of bottlenose dolphins. The collaboration with NUWC at AUTEC has resulted in their developing the capability of tracking beaked whales acoustically in real-time.

There is a particularly high Navy need to determine responses of deep-diving toothed whales to anthropogenic noise: there are anecdotal reports that several species may be sensitive to military sonar sounds, and there is no evidence available for setting safe exposure levels. There are several associations of atypical mass strandings of beaked whales with naval maneuvers or sonar operations, but no cause and effect relation has been established (Simmonds and Lopez-Jurado 1991; Frantzis 1998). These atypical mass strandings may involve more than ten animals distributed over tens of kilometers of coastline within a few hours of sonar transmissions (Cox et al. 2006; Evans & England 2001; Martín et al. 2004; Frantzis 1998; Martín et al. 2004; Simmonds and Lopez-Jurado, 1991). Other known causes of stranding have been ruled out in some cases, and sonar sounds spread rapidly enough over broad enough ranges to be a potential trigger for strandings with the observed timing and distribution (D'Amico, 1998; Evans and England 2001). Ignorance of safe exposure levels for deep diving whales hinders assessment of the potential impact of Navy active acoustic operations, a requirement under NEPA, and it hinders estimating the potential number of "takes" under the MMPA and ESA.

Research on the behavioral effects of noise on deep diving whales has suffered from a lack of methods to observe behavior in sufficient detail. Many deep diving species are visible only when they are breathing at the surface, which represents <5% of the time (Tyack et al. 2006; Watwood et al. 2006), so visual observations are seldom adequate. The part of this project related to preparing for effects studies is based upon the DTAG, which has been designed to monitor the sounds a whale makes, to measure the received level of stimuli at the whale and to track behavior including potential disturbance responses of these deep diving species throughout their dive cycle. Analysis from this work of the dive behavior of both *Ziphius cavirostris* (Zc)and *Mesoplodon densirostris* (Md) (Tyack et al. 2006) has helped narrow hypotheses relating diving

behavior to risk of decompression (Fernandez et al. 2005; Jepson et al. 2003; Jepson et al. 2005). The team was able to define an unusual behavioral response of a *Ziphius* to a ship passing over a diving whale (Aguilar et al. 2006), and has defined an approach for studying responses of tagged beaked whales to naval sounds (Appendices D and E).

1.4 Field work tagging beaked whales

The initial phase of the tagging component of this project involved the first attempts to attach these tags on deep-diving beaked whales. Field sites were established in the Ligurian Sea and Canary Islands after initial field efforts in North American sites near Navy underwater ranges suggested that they were less promising for initiating field work. The first beaked whale was tagged in October 2002 in the Ligurian Sea. The team has continued to tag *Ziphius cavirostris* there in 2003, 2004 and 2005. *Mesoplodon densirostris* were tagged in El Hierro, Canary Islands in the spring of 2003, 2004 and 2005. While it remains time consuming to obtain opportunities to tag beaked whales in either site, the team has learned how to do this routinely, and has built up an excellent data base of tagged whales. There is now a total of 10 tagged *Ziphius cavirostris* and 7 tagged *Mesoplodon densirostris*. This yields a total of 80 hours of tag data from *Ziphius* and 70 hours from *Mesoplodon*.

The initial goals of the SERDP field work also included tagging whales within the AUTEC range to estimate the probability of range sensors detecting their vocalizations. During March of 2002, field work was conducted at the AUTEC range. The team was able to tag pilot whales, melon-headed whales, and rough-toothed dolphins, which were also detected on range hydrophones, but the lack of knowledge concerning the vocalizations of beaked whales made it difficult for personnel monitoring the range hydrophone array to help biologists on vessels to find beaked whales. Another field effort was attempted at Abaco in May 2004 in collaboration with the BMMS, which knew from previous sighting data where to expect *Ziphius cavirostris* and *Mesoplodon densirostris*. However, it was not until the clicks of beaked whales were characterized in European field sites, that the full potential for field work at AUTEC was realized. Audio recordings of these beaked whale clicks were sent to David Moretti’s group at NUWC which incorporated a beaked whale detector into their real time monitoring system for the AUTEC range. The team has now conducted several ground truthing cruises at AUTEC, and on all 13 of the occasions when range monitors identified beaked whale clicks, their location data led the vessels to sight beaked whales. They were even able to conduct a joint follow, with the range monitors following a whale when it was foraging at depth, notifying the visual observers when it stopped clicking and headed towards the surface, and with the visual observers sighting the whale and notifying the range monitors when it dove and was likely to start clicking. These successes finally created a high potential for tagging work at AUTEC.

2. Objective

The basic goals of this project were (1) monitor the location, abundance and behavior of marine mammals, and (2) evaluate the short and long-term impacts of DoD activities on marine mammals.

2.1 Monitoring

Assessing the probability of detecting animals using passive acoustics requires the following information: (1) The probability of an animal remaining silent, and how this may vary with age and sex; (2) the source level and spectral characteristics of the calls of each species; and (3) the precise times and locations for all vocalizations of animals tracked within the range (to validate the passive acoustics).

The technical approach for meeting these data needs involved a sophisticated whale tag, the DTAG. The DTAG uses a hydrophone on the animal to obtain a continuous unbiased record of the vocalizations of the tagged individual, providing the precise times and waveforms of these vocalizations identified to individual and species (Johnson & Tyack 2003).

One of the highest priority taxa for monitoring was beaked whale species that have been reported to strand during naval sonar exercises. The first step in meeting this objective was to modify the initial DTAG, whose attachment had been developed for large baleen and sperm whales, for use with beaked whales. The second step was to develop field sites to work with beaked whales. The third step was to learn how to tag these animals. The fourth step was to obtain far-field on-axis recordings of their signals. The fifth step was to model the source level and beampattern of their calls. Once this was achieved, it was possible to model the probability of detecting these whales as a function of range or sensor spacing. Each step was successfully achieved in this project.

Several Navy ranges are developing an advanced acoustic detection and localization capability for marine mammals. One of the objectives proposed for this project was to collaborate with NUWC and AUTEC personnel to test and validate the performance of passive acoustic monitoring of marine mammals on a Navy range. Once farfield on-axis tag data were recorded on the DTAG, these data were distributed to these groups which they were able to use to develop a beaked whale click detector for their marine mammal monitoring software for the AUTEC range hydrophones. Once this detector was installed, beaked whale clicks have been routinely detected and localized. Several joint field exercises were then conducted with NUWC and AUTEC personnel to validate their passive acoustic monitoring. The ESWTR was another priority range for the research. The passive monitoring arrays are not fully operational at ESWTR, so visual surveys and acoustic monitoring of cetaceans were conducted near ESWTR at Onslow Bay.

2.2 Evaluating the Short and Long-Term Effects of Noise from Defense Activities

2.2.1 Short-term Effects

The acoustic recording tag is not only useful for validating passive acoustic monitoring. It also has sensors that sample the orientation and movement of the tagged whale. This makes it possible not only to monitor sound as heard by the whale, but also to monitor the responses of deep diving whales to human-generated signals of relevance to the Navy. Short-term effects can either be studied by tagging whales near human sound sources or by controlled exposure experiments (CEEs). The short-term responses of a beaked whale were evaluated in an adventitious exposure in which a tagged *Ziphius* was exposed to sounds from a passing ship. This whale was exposed to unexpectedly high levels of high frequency sound from the ship propulsion. It broke off a foraging dive and returned early to the surface. As part of the SERDP project, papers were written to define the CEE approach (Tyack et al. 2004) and a workshop was conducted at the European Cetacean Society on beaked whales and sonar (Tyack & Johnson 2003). Peter Tyack participated in several other workshops on this issue, including one sponsored by the US Marine Mammal Commission, which unanimously recommended CEEs to beaked whales as the top priority research topic for this issue (Cox et al. 2006). A white paper on CEEs to beaked whales requested by the SERDP In-Progress Review has also been submitted. This kind of research on short-term impacts of naval sound sources will provide critical data for developing new methods and protocols for operating these sources in ways that comply with federal environmental laws.

2.2.2 Long-term Effects

Passive acoustic monitoring is well suited to evaluating the long-term impact of naval operations. Once this technique has been tested and validated, it offers a non-invasive, cost-effective method to monitor vocal behavior and distribution of vocalizing animals before, during, and after sound transmission, where the time periods can range from seconds to years. This capability will be of greater usefulness, the greater the extent to which studies of short-term impacts have elucidated the causal mechanisms linking sonar exposure to injury and/or stranding, and as they provide details of behavioral responses that may be detected using passive acoustic monitoring. NUWC had already demonstrated a capability for monitoring marine mammal species such as sperm whales on the AUTEC range, and the collaboration supported by this project between WHOI and NUWC at AUTEC created a unique opportunity for passive acoustic monitoring for beaked whales. The passive acoustic monitoring of vocalizing marine mammals that was validated in this project offers the best opportunity to monitor long-term effects of noise in a fixed habitat such as a navy underwater range. ONR has now funded NUWC to conduct this kind of monitoring consistently for several years at AUTEC, both when no operations are ongoing, and while naval sources are active. This study can test for changes in the distribution or vocal behavior of animals before, during, and after sound transmissions, on time scales from seconds to years.

3. Background

3.1 Effects of Anthropogenic Sound on Marine Mammals

There has been increasing concern about the impact of anthropogenic underwater sound on acoustically sensitive animals such as marine mammals. The National Academy of Sciences has produced four reports on this topic since 1994 (NRC 2003). Over the past century, economic and technological developments have increased the human contribution to ambient noise in the ocean. Shipping is the overwhelmingly dominant source of anthropogenic noise in the ocean (NRC 1994, 2003). There are few measurements tracking changes in shipping noise over decades (Andrew et al. 2002); however, shipping noise is generally reported to have increased ambient noise levels by 10 dB from 1950 to 1975 (Urick 1986). A wide variety of artificial sound sources also contribute to the ambient sound field, including explosive sources, sonar, seismic exploration, and acoustic telemetry. There is growing evidence that man-made sounds can disturb marine mammals, and this issue was given an extensive review about a decade ago (Richardson et al. 1995). Observed responses include silencing, disruption of activity, and movement away from the source (Chapter 9, Richardson et al. 1995). The zone of influence of a sound source depends upon its level, its frequency spectrum, and upon the conditions for sound propagation near the source (Chapter 10, Richardson et al. 1995). Sound carries so well underwater that animals have been shown to show strong avoidance at ranges many tens of kilometers away from a loud acoustic source (Cosens and Dueck 1988; LGL & Greeneridge 1986, Finley et al. 1990), and there is no *a priori* reason to rule out effects at even greater ranges. Marine mammals rely on sound for communication, orientation, and detection of predators and prey; disruption of any of these functions would interfere with normal activities and behavior. This has also raised concern that, along with short-term impacts of single sources, increasing noise may also have long-term impacts as a form of habitat degradation.

Marine mammals are protected by three Acts of Congress: the Marine Mammal Protection Act of 1972 (MMPA), the Endangered Species Act of 1973 (ESA), and the National Environmental Protection Act (NEPA). The MMPA prohibits any person or vessel subject to the jurisdiction of the United States to take a marine mammal where "take" is defined as "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal." Harassment in turn has been defined as **a**ny act of pursuit, torment, or annoyance which —

1. Level A Harassment - has the potential to injure a marine mammal or marine mammal stock in the wild; or
2. Level B Harassment - has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption or behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering.

The Defense Authorization Act of 2004 redefined harassment for military activities as "is likely to disturb" marine mammals to the extent that their natural behavior patterns "are abandoned or significantly altered." Taking by harassment is regulated under the MMPA, but harassment of marine mammals has proven difficult to define in a biologically meaningful manner. Most of the

large whale species were placed on the US Endangered Species List in 1970. The ESA has a prohibition on taking that is similar to that of MMPA.

The DoD, as a branch of the Federal government, is required under NEPA to evaluate the potential environmental impacts of major actions or activities. The need for environmental compliance regarding marine mammals and noise creates a need to develop methods to assess the impacts on marine mammal populations. SERDP, ONR, and CNO N45 have made major progress in the past decade on this issue. It is now known what levels of sound may start to cause effects on hearing in dolphins and seals (Kastak and Schusterman 1998; Schlundt et al. 2000; Finneran et al. 2002). Figure 1 (courtesy of James Finneran, US Navy marine mammal program at Space and Naval Warfare Systems Command (SPAWAR)) summarizes the results of a series of experiments measuring the peak pressure and duration of signals either associated with a reduction in hearing sensitivity (red symbols) or no detectable change (green symbols). While this research safely defines a conservative threshold for auditory damage, Cox et al. (2006) suggest that these thresholds may not be appropriate to define risk of injury for beaked whales exposed to military sonar.

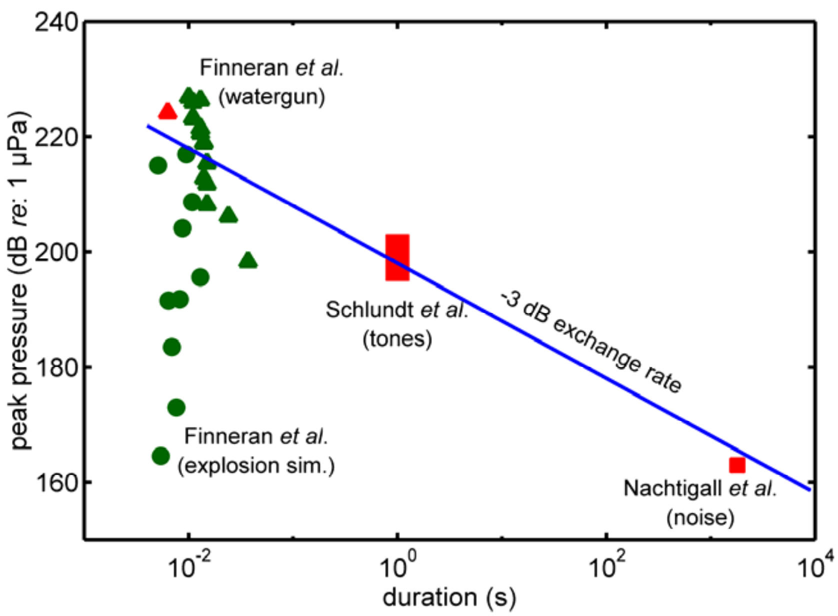


Figure 1. Summary of temporary threshold shift experiments on toothed whales relating peak pressure levels to duration (courtesy of James Finneran, SPAWAR).

As the SON on marine mammal monitoring indicates, there is now an urgent need for techniques to monitor toothed whales and their reactions to sound. Toothed whales are more common than the baleen whales and have hearing and vocalization ranges extending to considerably higher frequencies. Several Navy ranges have installed broad bandwidth hydrophones that are well-suited to capturing the high frequency calls of toothed whales. Methods for detection and localization of these calls are being developed by NUWC and other research groups. If these methods are validated, they will provide important and cost-effective monitoring capabilities. They will also provide a means for monitoring the long term effects of noise in a fixed habitat.

The SON on marine mammal monitoring lists the requirement for verifying the probability of detecting marine mammals, and the probability of correct classification, using acoustic or non-visual monitoring. The probability of detecting an animal using passive acoustics is the product of two conditional probabilities: (i) the probability of vocalization, which will vary with species, gender, age, and activity, and (ii) the probability of detecting a given call. Clearly, information is needed on:

- The SL and spectral characteristics of the calls of each species.
- The probability of an animal remaining silent, and how this varies with age and sex.
- The identification and location of individual vocalizing animals that are being tracked using range hydrophones.

The research conducted for this project depends upon the DTAG, which was developed with support from ONR, and which provides high-fidelity, calibrated on-animal recordings of vocalizations. The DTAG is the optimal method, and in many cases the only method, to obtain data on how often an animal vocalizes and to obtain a clean record of the vocalization with certain species identification. The tag provides the precise times and waveforms of vocalizations together with the depth and orientation of the animal and a number of behavioral cues. In this Background section, earlier work in this area will be reviewed.

The second area of need listed in the SON on marine mammal monitoring, is an assessment of the short and long-term impacts of defense activities on marine mammals. During the past decade, there has been growing clarification that the "harassment" prohibited by the MMPA and ESA should not refer to any detectable change in behavior, but rather to meaningful disruptions of critical activities that might conceivably affect demography (NRC 1994, 2003). This clarification suggests that concerns about short-term impacts caused by exposure to sound should focus particularly on situations where brief interruptions could cause harm, such as when mother and young are separated, or when there are suggestions of strong or prolonged reactions to noise.

There is a particularly high Navy need to determine responses of deep-diving toothed whales to anthropogenic noise: there is clear evidence that some species are sensitive to military sonar sounds, and there is no evidence available for setting safe exposure levels. Watkins et al. (1985) provided evidence of sperm whales silencing and moving away when naval sonars were operating in the 3-9 kHz range. There are several associations of mass strandings of beaked whales with naval maneuvers or sonar operations (Simmonds and Lopez-Jurado 1991; Frantzis 1998), but the causal chain of events leading from sonar exposure to stranding is unknown (Cox et al. 2006). NURC convened a panel to review the stranding reported by Frantzis (1998) and concluded: "An acoustic link can neither be clearly established nor eliminated as a direct or indirect cause for the May 1996 strandings" (D'Amico 1998). Our ignorance of safe exposure levels for deep diving whales hinders assessment of the potential impact of Navy active acoustic operations, a requirement under NEPA, and it hinders estimating the potential number of "takes" under the MMPA and ESA.

Research on the behavioral effects of noise on deep diving whales has suffered from a lack of methods to observe behavior in sufficient detail. Many deep diving species are visible for less than 5% of the time, when they are breathing at the surface, so visual observations are seldom

adequate. Passive acoustic monitoring of beaked whales has been hindered by ignorance of the sounds they produce. Moreover, sperm whales have been reported to silence in response to anthropogenic sounds (Watkins 1985; Watkins & Schevill 1975), so passive acoustic tracking may not be adequate for studies on responses to sound in this species. An acoustic recording tag is the critical tool for monitoring potential disturbance responses of these deep diving species.

3.2 Initial Acoustic Tag Field Work

Early examples of acoustic recording tags are those of Burgess et al. (1998), developed for deep-diving elephant seals, and Costa et al. (2003), who used such a tag to study the effects of an Acoustic Thermometry of Ocean Climate (ATOC) transmitter on the dive patterns of seals. Peter Tyack has been developing tags to identify the vocalizations of cetaceans since 1982 at WHOI (Tyack 1985, Tyack and Recchia 1991, Burgess et al. 1998). This effort yielded a major breakthrough in 1996 when electronics engineer, Mark Johnson, joined the team collaborating to develop acoustic recording tags. An ONR-funded effort to drastically reduce the size, and increase the capabilities, of acoustic recording tags resulted in the development of the DTAG in 1999. The DTAGV1 used solid-state memory in place of moving magnetic tape or disks to record data and so could be encapsulated in epoxy resin. The DTAG uses a low-power digital signal processor to combine audio from a hydrophone with sensor measurements, and stream the data to a non-volatile memory array. The sensors include hydrostatic pressure, temperature, and three-axis magnetometers and accelerometers, which can measure pitch, roll, compass heading. The complete electronics package for the DTAGV1 measured 4” x 2” x 0.8”. The DTAG is fully programmable and communicates with a personal computer (PC) using an infrared (IR) wireless link. Programs and parameters, such as sampling-rate, audio gain, and release time, are loaded into non-volatile memory on the tag using the IR interface. This can be done in the field using a laptop computer or personal digital assistant (PDA) allowing rapid configuration of the tag for prevailing conditions. After recovery of the tag, the recorded data are off-loaded from the tag using the IR link at a speed of 4 megabit-per-second (Mbit/s). At this rate, the 400 Megabyte (MB) memory on the V1 tag could be off-loaded in about 20 minutes. Diagnostic functions can also be initiated from the IR link to check the operation and calibration of the tag.

The first field work with the DTAG involved attaching the tag to slow moving right whales. The team adopted an attachment technique based upon a cantilevered carbon fiber pole developed by Miller et al. (1998). In its first deployment, on northern right whales in the Bay of Fundy, the DTAG produced a phenomenal data set. The tag was programmed to sample audio continuously at 16 kiloHertz (kHz), giving an audio bandwidth of 50 Hertz (Hz) to 6 kHz. The non-acoustic sensors were sampled at 23 Hz per channel. With these settings, the recording time was 4.5 hours, sufficient to determine baseline behavior of the animal, and its response to a controlled sound exposure. The tag was deployed on 5 right whales using a non-invasive suction cup attachment (Figure 2) with a longevity of up to 9 hours. A contact hydrophone, placed in one of the suction cups, yielded high quality recordings of vocalizations, motion noise, as well as a variety of non-vocal animal sounds (Figure 3). The high sensor sampling rate meant that individual fluke strokes could be resolved in detail providing a unique insight into the sub-surface behavior and energetics of the whale (Figure 4). These high sample rates are unique to the DTAG, and provide critically detailed data on behavioral responses.

Figure 2. DTAG attached to a right whale in the Bay of Fundy, August 1999. Photo Credit: WHOI. This research was conducted under US NMFS permit no. 1014 and Canadian permit DFO no. 2000-489.

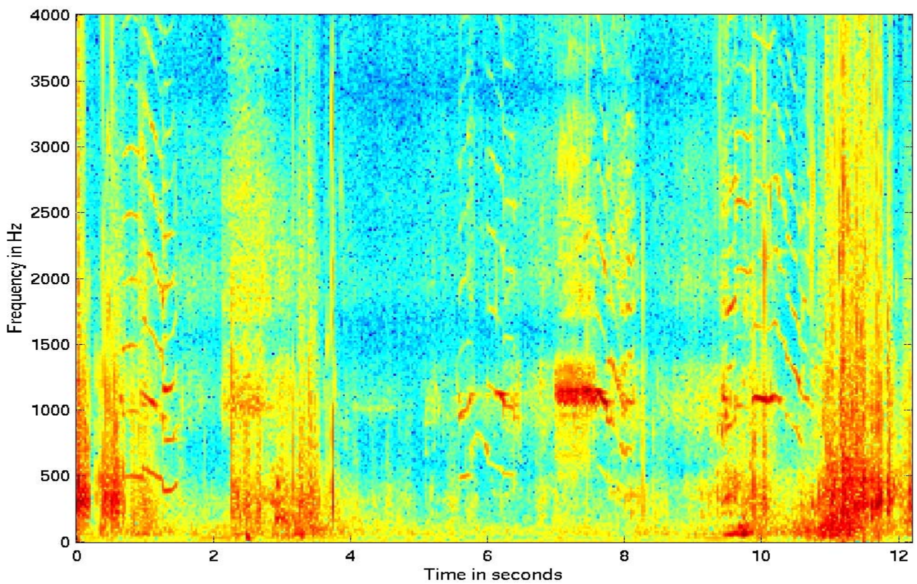


Figure 3. Spectrogram of a sequence of right whale vocalizations, captured with the DTAG, August 1999.

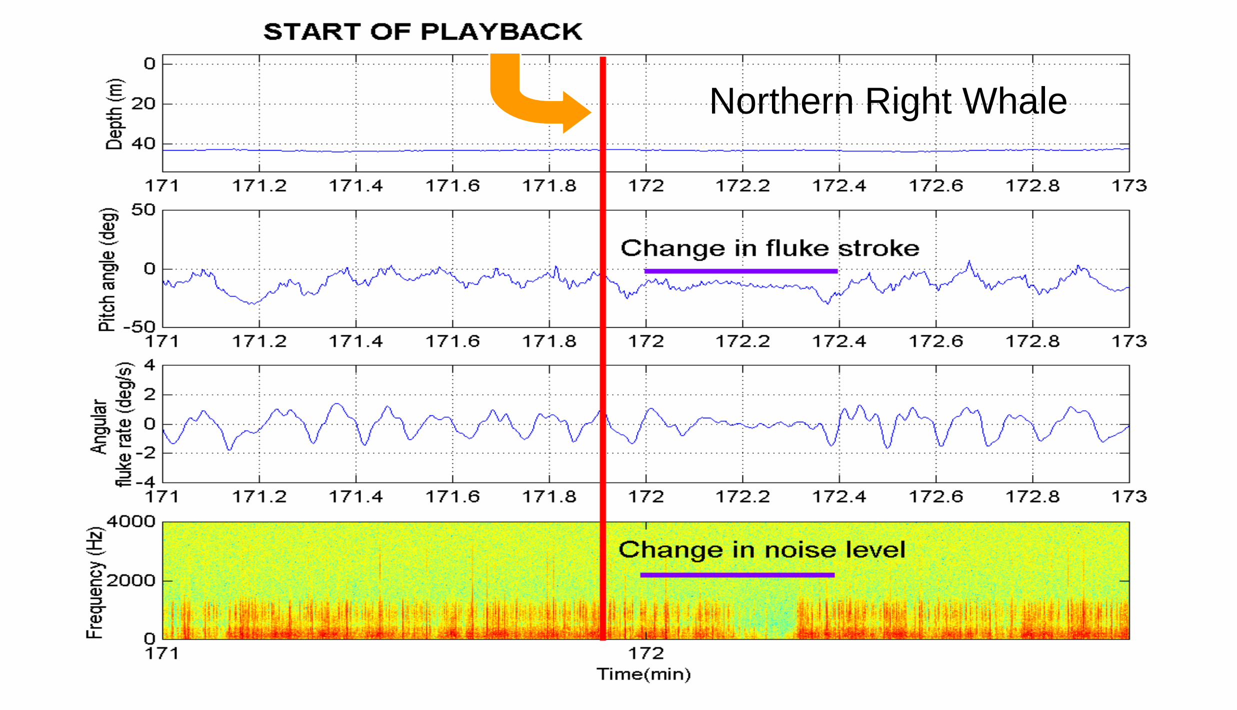


Figure 4. Dive depth, pitch angle, fluking rate, and acoustic records from a DTAG deployment on a right whale, 1999. The whale appears to have paused in its swimming after a sound playback, leading to a reduction in flow noise on the tag, and presumably for the whale's hearing.

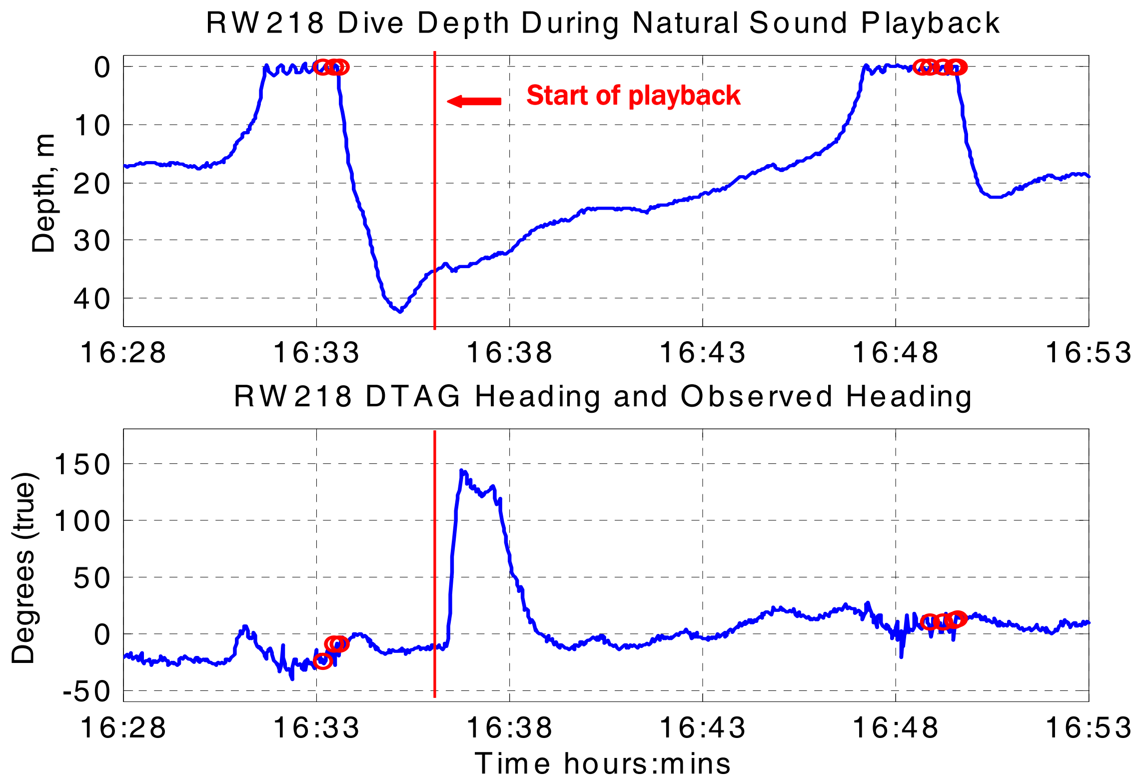


Figure 5. Temporary change in heading of a right whale after initiation of a playback experiment. The red circles represent surface sightings.

The tag contains a three axis magnetometer and a three axis accelerometer. This allows one to measure the pitch, roll, and heading of the tagged whale. Figure 4 shows how oscillations in the pitch data can be used to measure the fluking rate of the animal, giving details of its swimming behavior. This whale appeared to pause in its swimming immediately after a sound playback, leading to a reduction in the flow noise. By slowing down, the whale probably reduced the noise floor for its own hearing as well. The heading data also show clear responses to playback of right whale vocalizations as well. Figure 5 shows a pronounced change in heading after the start of playback. The whale went back to its previous heading after about 1 minute, while it was still at a depth of about 30 meters (m). Therefore, this clear but short response could not have been detected by visual observers at the surface, even for a baleen whale that does not dive for very long by cetacean standards.

After developing the field approach for tagging right whales, which move slowly and spend long periods of time at the surface, the focus was moved to sperm whales, which are a deep-diving toothed whale. Given how seldom one can see these whales at the surface, the benefit of continuous sampling of a tagged whale is even greater. The initial field efforts focusing on sperm whales were in 2000 in the Ligurian Sea and the Gulf of Mexico. Figure 6 illustrates attachment of the tag to a sperm whale using the cantilevered pole. The dive profile of a sperm whale tagged during these early efforts is plotted in Figure 7, which shows a series of deep foraging dives followed by a surface interval.

Figure 6. Mark Johnson tagging a sperm whale in the Gulf of Mexico with a cantilevered carbon fiber pole. Photo Credit: WHOI. Research conducted under US NMFS permit no. 981-1578-02.

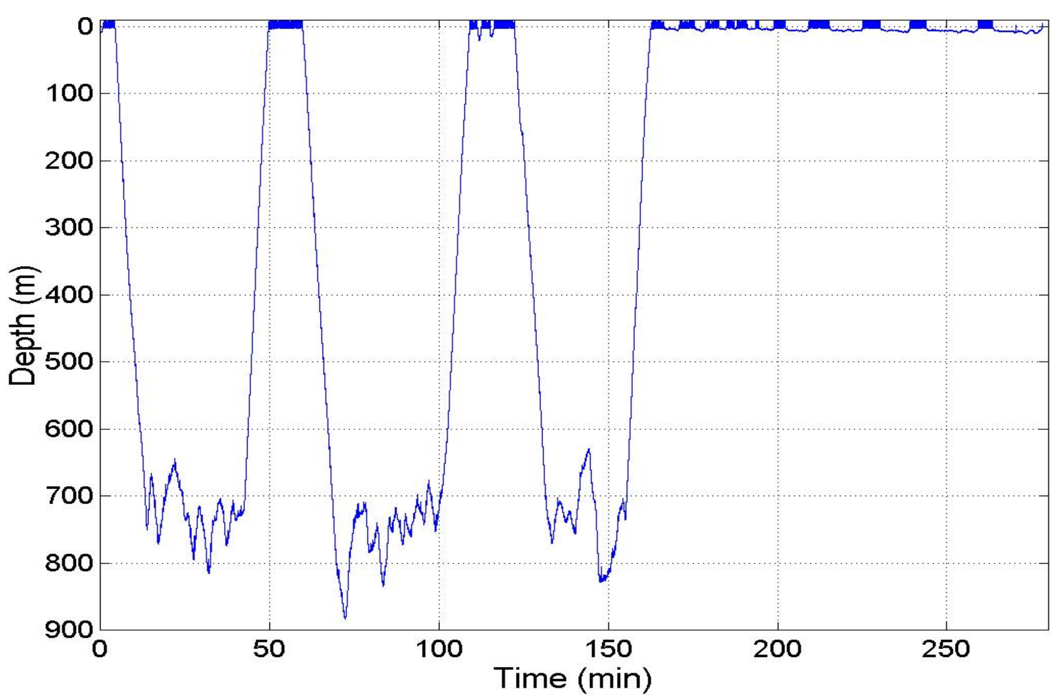


Figure 7. Dive profile of a DTAGged sperm whale.

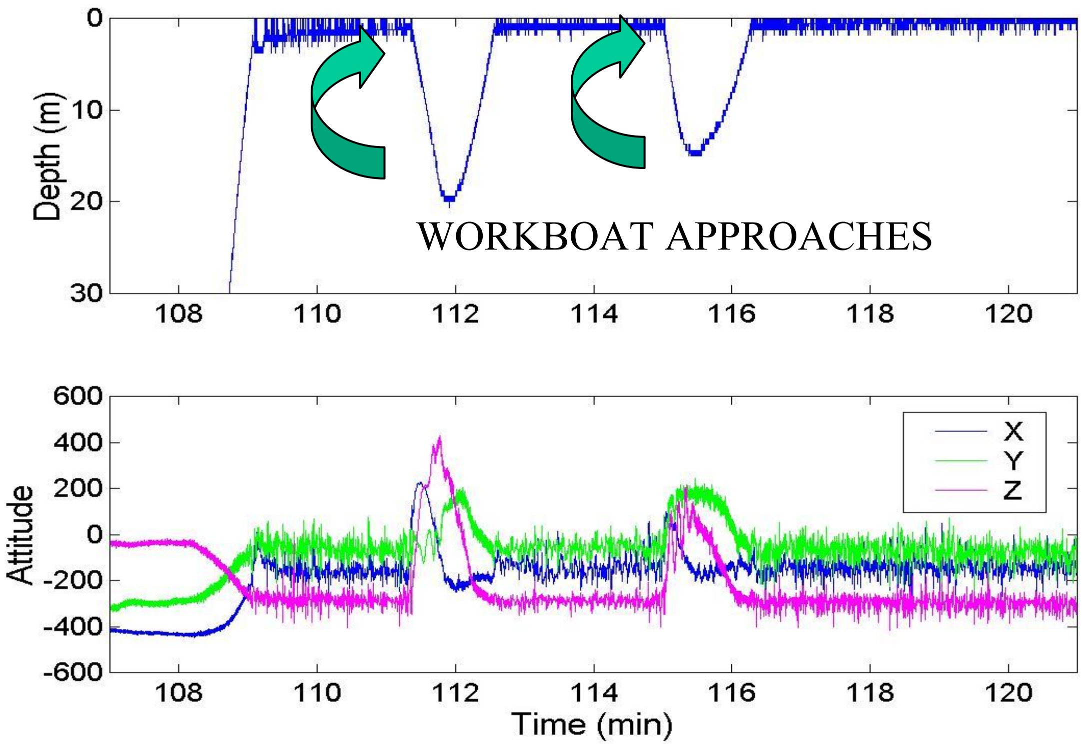


Figure 8. Raw orientation sensor data (X,Y,Z) and dive response of a tagged sperm whale to approach of a small workboat.

One of the first things noticed with the tag data was how sensitive it was for measuring responses of whales to human disturbance. For example, on the first surfacing after tagging, the tag attachment vessel approached the tagged sperm whale twice. Experienced visual observers on the tag boat did not notice a response, but it is obvious from Figure 8 that the whale made a shallow dive after each approach. This kind of short shallow dive is very unusual in the control data from undisturbed whales.

During the first field season tagging sperm whales and testing whether a mid-frequency sonar could be used to detect whales, a cessation of fluking and change in orientation was noticed as the tagged whale dove from the surface to a depth where the sonar pings were more obvious (Malakoff 2001). This kind of short pause in swimming is similar to that seen during playbacks to right whales, and may indicate a listening response, in which the animal reduces the noise from swimming and may reorient in order to improve its ability to listen to a sound.

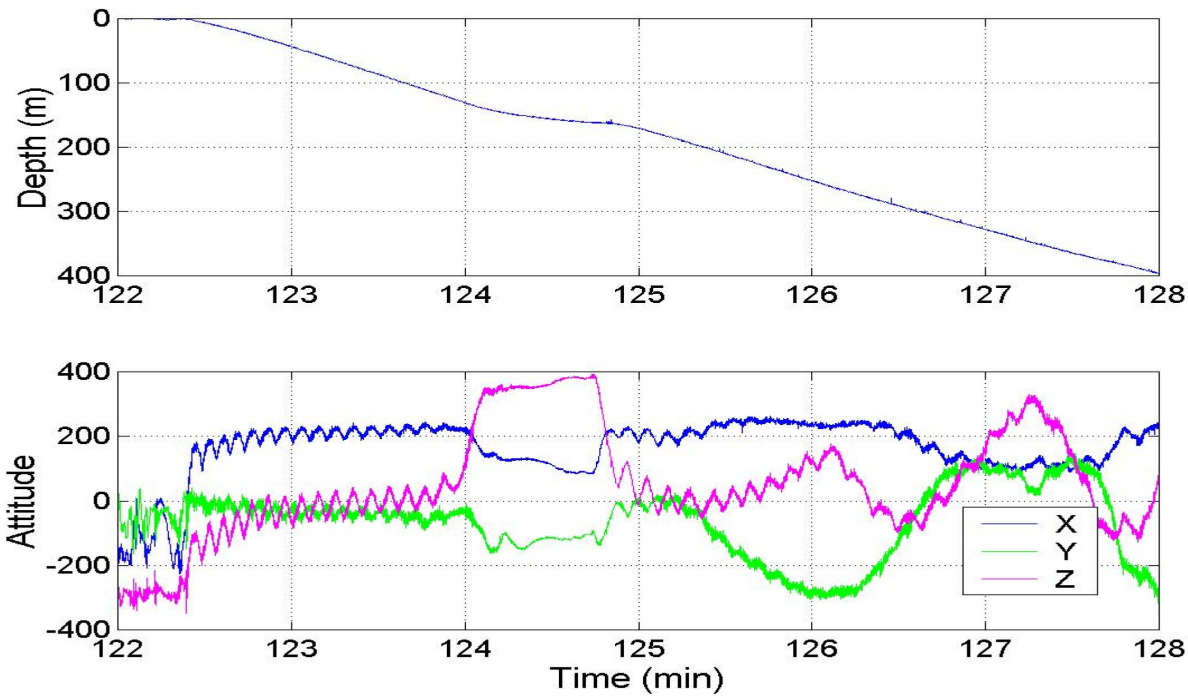


Figure 9. Raw orientation sensor data (X,Y,Z) for the initial descent phase of a sperm whale dive. As this whale dove, the received level of sonar pings increased due to propagation conditions.

3.3 Controlled Exposure Experiments

The problem with these kinds of single opportunistic observations is that it is very difficult to test whether the sound exposure caused the reaction. Experimental techniques are required to answer this question conclusively. The kind of experiment used to test whether a specific dosage of sound causes a specific behavioral reaction is called a Controlled Exposure Experiment (CEE) (Tyack et al. 2004). The key for this kind of experiment is to accumulate data on a series of individual whale subjects, whose responses to controlled exposures of a sound can be analyzed statistically.

One of the classic approaches to a CEE for animals that surface regularly involves observing the whales from shore stations, using a theodolite to pinpoint the location of each surfacing (Malme et al. 1983, 1984). The right cell of Figure 10 shows tracks in blue of groups of gray whales as they migrate past the central California coast. The left cell of Figure 10 shows tracks of whales exposed to signals from the SURTASS LFA sonar at a source level of 185 dB rms re 1 μPa. It should be obvious that the whales deviate around the source, showing a clear avoidance reaction. By controlling for all factors other than the sonar sound, it is possible to demonstrate that it is the sonar pings that cause this avoidance response. By playing back the sonar sounds at different source levels it is also possible to demonstrate that the whales are not responding to the distance to the source, but rather to the received level (RL) of the sonar signal. Figure 11 plots an avoidance index as a function of RL at the whale, pooling CEEs using source levels from 170-

185 dB. The confidence intervals are generated by a Monte Carlo simulation, and show that the sample sizes for this work enable high confidence about the dose:response relationship over the 15-20 dB range of greatest interest.

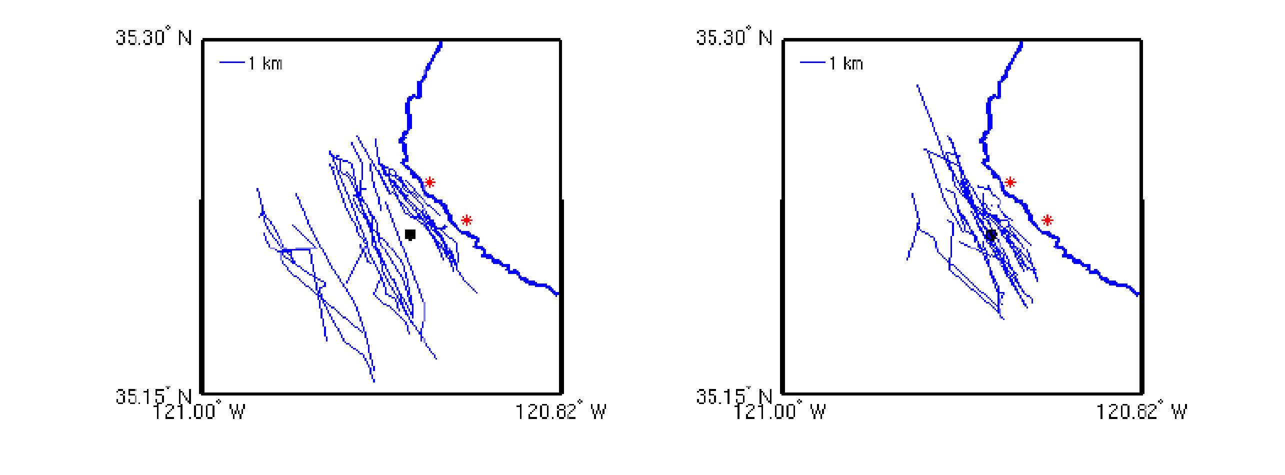


Figure 10. Left cell: Avoidance responses of gray whales migrating past the central California coast to a low frequency sonar source (indicated by the black square) operating at a SL of 185 dB rms re 1 μPa compared to (Right cell) control observations with the source turned off. Red dots indicate the positions of the on-shore observation sites.

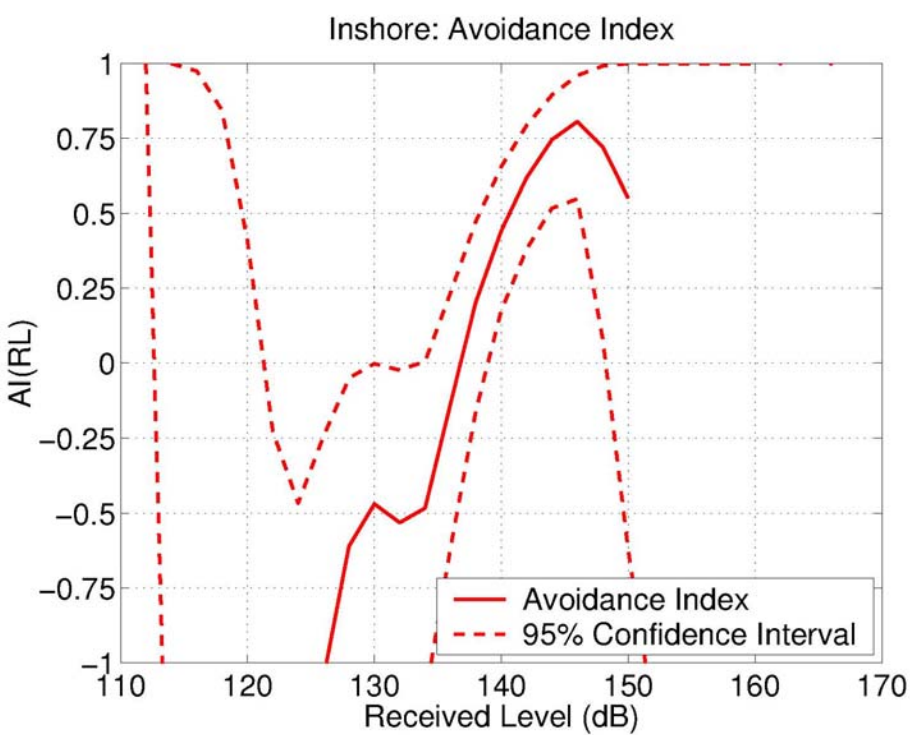


Figure 11. Statistical analysis of avoidance responses of migrating gray whales to low frequency sonar. Courtesy of Prof. John Buck, University of Massachusetts Dartmouth.

This classic approach is not possible for deep diving whales that occur far from shore and that are seldom visible. Starting in 2000, the WHOI tagging team started two projects to prepare a design for CEEs to deep divers. One project in the Ligurian Sea involved a mid-frequency sonar developed as a potential whale-finding sonar. The other in the Gulf of Mexico involved airguns used for seismic exploration. The first phase of these experiments involved learning how to tag sperm whales, while simultaneously following them with visual observation and passive acoustic monitoring. After several cruises devoted to this task, controlled exposures were added, which had a target exposure level at the whale.

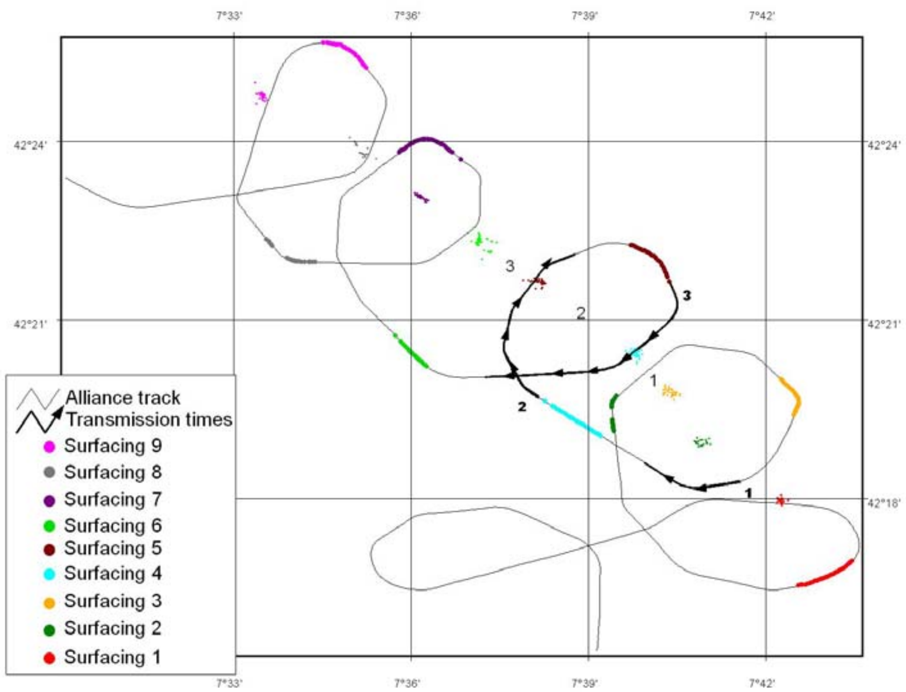


Figure 12. Map of CEE to a tagged sperm whale using a mid-frequency sonar. The sound source vessel was the "Alliance" whose track (thin line) is shown. Courtesy of NATO Undersea Research Centre.

Figure 12 illustrates the ship's track as the thin black line. Colored portions of the line correspond to times when the visual observers sighted the whale at the dots with the corresponding color. The thicker portions of the line mark periods when the ship was transmitting brief sonar pings every 15 seconds. Figure 13 is a spectrogram of the sonar pings as recorded on the whale. One can see the direct arrival as well as bottom and surface reflections. It is common that the signal as received at the whale is modified by propagation through the ocean. NURC has extensive experience with modeling this kind of sound propagation, and engineers on the ship worked with whale monitors to adjust the SL of the sonar to ensure that a maximum received level at the tagged whale was not exceeded. The terms of the permit under which this work was done stated that the whales would not be exposed to received levels greater than 160 dB rms re 1 μPa. Figure 14 plots the sound level of each sonar ping received at the whale as a function of time. At the start, transmission was slowly ramped up from a source level of 160 dB rms re 1 μPa to a level sufficient to achieve the goal level. In this experiment, a primary goal was

to test whether the sonar pings could be used to detect echoes from the whale back at the ship. During the second dive centered around 1030 Zulu (Z), the source level was held steady, and with a relatively stable range from the sonar to the whale, the received level at the whale was near a stable level near 130 dB re 1 μPa. The scatter of points slightly lower than 130 dB may reflect times when the whale rolled so that the body of the whale was between the tag and the source, shadowing the sound to some extent. These CEE experiments demonstrated the ability of the ship-based team to find, tag, and follow whale subjects, and to maintain a pre-determined exposure level on the whale. Not very many of these preliminary experiments were conducted, but as Figure 15 shows, there was no obvious major change in dive behavior comparing exposure to pre-exposure or post-exposure periods.

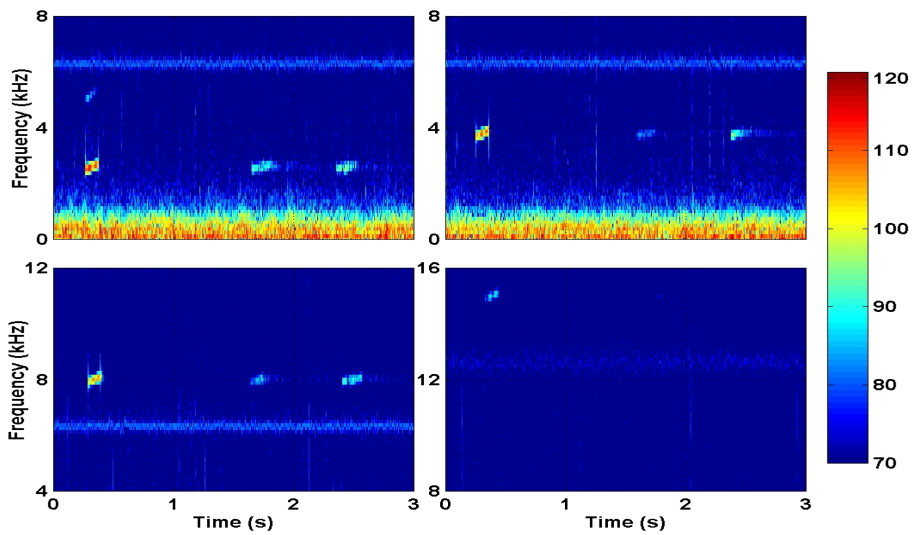


Figure 13. Sounds of mid-frequency sonar pings as recorded on a tagged sperm whale. Courtesy of NATO Undersea Research Centre.

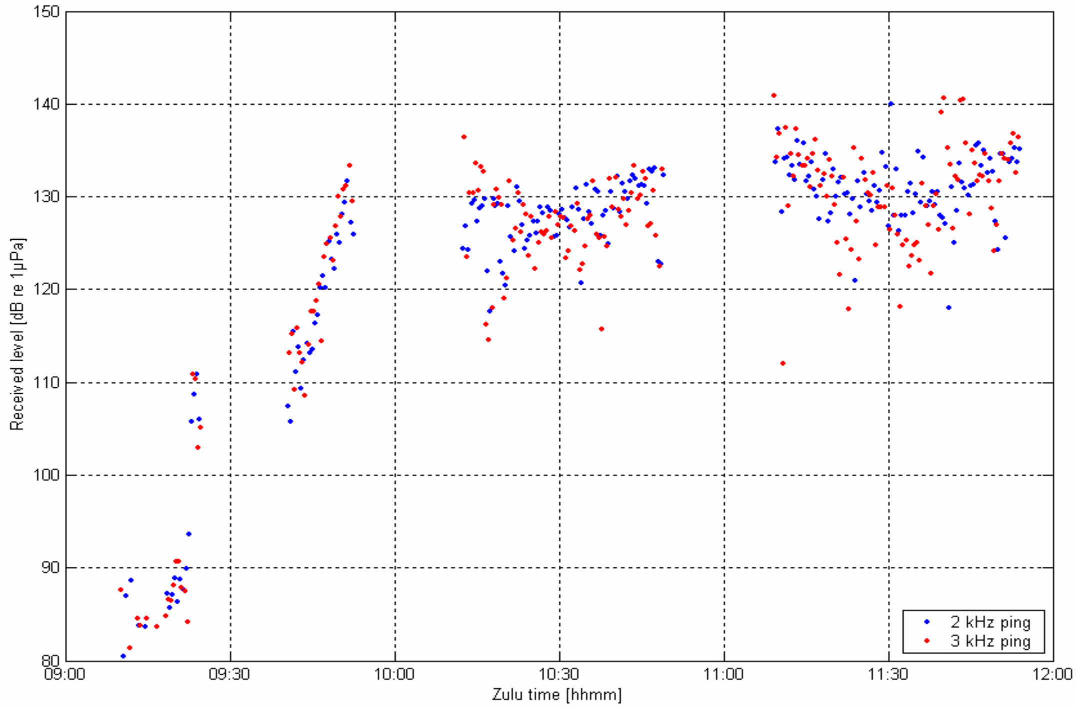


Figure 14. Received Level of sonar pings as recorded on a tagged sperm whale. Courtesy of NATO Undersea Research Centre.

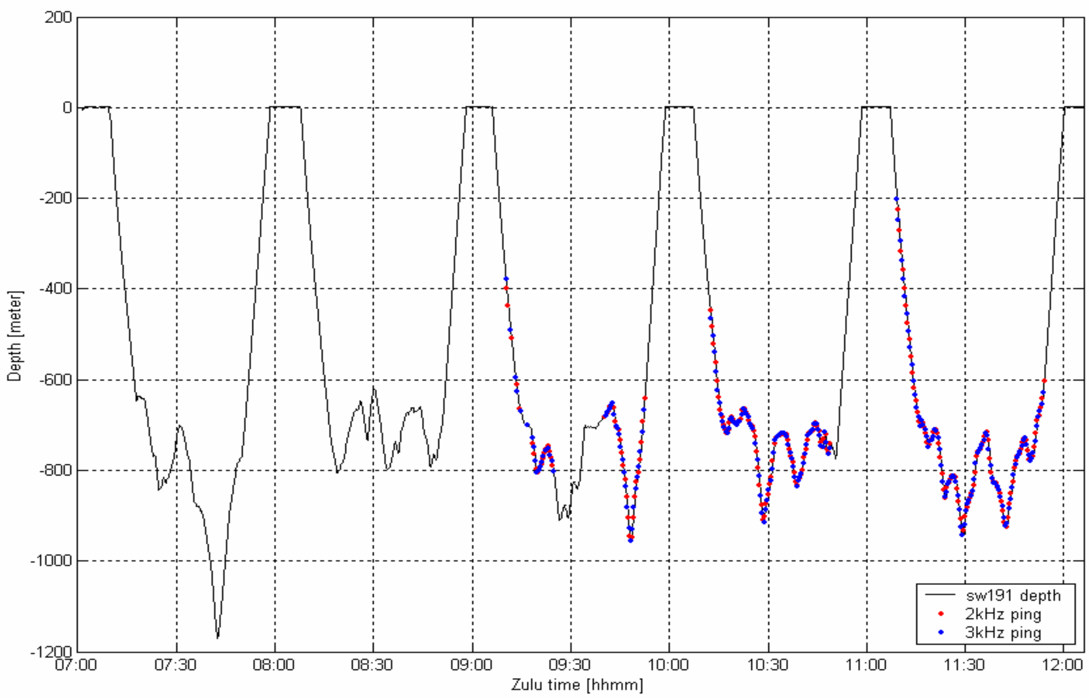


Figure 15. Dive profile of tagged sperm whale with times of sonar pings illustrated with red and blue dots. Courtesy of NATO Undersea Research Centre.

One of the most important steps required for the proposed research was learning how to tag beaked whales with the DTAG. Prior to our work, the only successful tagging of any beaked whale was the work of Hooker & Baird (1999) who successfully tagged northern bottlenose whales in the Gully off Nova Scotia. This work used a suction cup time depth recorder, and their success with suction cup tagging gave some hope of developing the capability of tagging other species of beaked whales.

4. Materials and Methods

As discussed in the background section, the primary method proposed for meeting the objectives of this project involved tagging beaked whales with a tag that could record both sound and behavior. The first steps required to enable this approach involved establishing field sites where beaked whales of the species reported to strand coincident with naval sonar exercises could be found frequently enough and in good enough sea conditions to learn how to tag them.

4.1 DTAG Deployment

The DTAG team spent considerable time modifying the sperm whale tagging protocol and identifying field sites and times of the year coinciding with the best weather for tag deployments and focal follows of beaked whales. Due to the short recording duration of the DTAG, and the desire to reduce disturbance of the focal animal to a minimum, a non-invasive suction cup tag attachment was used. The preferred method developed for approaching the whale for tagging involved approaching the whale slowly from behind in a small rigid hull inflatable boat (RHIB). The tag is delivered to the animal with a carbon fiber pole and 2 to 4 suction cups below the tag housing mate with the animal (Figure 16). The usual placement is in the center of the back on either side of the dorsal crest (where there is one). The tag releases after completing its recording by applying voltage to a nickel-chromium wire which then corrodes in seawater. A very high frequency (VHF) beacon on the tag makes location and tracking of the focal straightforward and speeds recovery of the tag after release. A highly reflective tape was applied to the outside of the tag housing to facilitate visual detection of the tag at night. This technique provides acoustic and behavioral data from the tagged animal as well as from conspecifics vocalizing nearby.

Figure 16. Attaching a tag to a beaked whale. Photo Credit: Marco Ballardini of BluWest. Research conducted under US NMFS Permit no. 981-1707-00.

During each tag deployment, the tagging team followed the focal whale, recording its position, heading, respiration times and surface behavior. Each sighting was fixed geographically as well as possible, using vessel global positioning system (GPS) location, and range and bearing from the vessel to the sighted whale. When possible, a hydrophone was towed from the observation vessel and the ambient sound was recorded. This recording is useful for checking for vocalizations from other animals, and could be used to qualify ship-based passive monitoring methods. These far-field data also were used to characterize the far-field beam pattern of the tagged whale (Zimmer et al. 2005b).The full data-set comprising DTAG audio recordings, sensor data, and surface observations, were provided to groups such as NUWC who are tasked with analyzing passive monitoring systems for the ranges.

4.2 Data Analysis and Delivery

A large time series was collected during each DTAG deployment, comprising over 5 million sensor measurements and up to 18 hours of audio recordings. This volume of data precludes rapid analysis and full analysis of the results from each field season takes several months. However, there are several compelling reasons to perform preliminary analyses of the data set in the field immediately after each deployment. First, to identify any strong reactions to a measured sound exposure and use this information to guide further field work. Secondly, to ensure that tag parameters such as audio gain and filter response are set correctly for the ambient noise environment. Finally, to detect equipment malfunction as early as possible. To this end, a suite of software tools was developed for field analysis of the DTAG data. These include a cepstral-based automatic vocalization detector, tools for visualizing and calibrating sensor data, and a spectral technique for detecting changes in fluke rate and dive pattern. In addition to field assessment of data quality, these tools provide a rapid means for highlighting sections of data warranting more detailed and less automatic analyses.

Soon after each field season, relevant tag data were distributed via compact disc (CD) to NUWC and other research groups. Audio data were in 16 bit .WAV file format. This audio format is a widely-used standard and freeware WAV players are available for Windows and Linux PCs. WAV files can also be read into MATLAB and similar analysis software packages for detailed examination and analyses. The audio sampling rate was chosen according to the vocalization frequency range of each target species. Higher sampling rates than usual were required to represent the full spectrum of beaked whale clicks, so the tag was modified to enable a sufficiently high sampling-rate of 192 kHz.

The sensor data were distributed in MATLAB .MAT format files. MATLAB is a standard software package used for analysis and visualization of time series and other data. MATLAB tools for processing the data sets are available on a WHOI website. Surface observations were combined using a spreadsheet program, such as Excel, or a geographical information system and distributed with the data set.

The data analyses performed by WHOI following each field season included the following key tasks:

(i) Scoring the audio recordings. A listener reviewed the entire set of recordings to determine cue points for vocalizations, surfacing, noisy blows, boat/playback sounds, and any other interesting features. Individual vocalizations were extracted and combined in a vocalization database.

(ii) Time aligning of surface observations and remote acoustic recordings with the DTAG data.

(iii) Identification of behavioral states during each focal follow. This is done by carefully considering the surface observations and DTAG measurements to estimate when the focal is sleeping, eating, diving, socializing, etc. Each behavioral state can then be parameterized in terms of fluke rate, depth, vocalization rate, and presence of other animals.

(iv) Scoring the effect of any exposure to human-made sounds in terms of a change in the pre, during, and post-exposure behavior of the focal. Responses were calibrated in terms of received sound level range to the sound source, initial behavior, sex, and age.

Where a potential response to sound exposure was indicated, an analysis was performed on how quickly they developed, how long they continued, and how they scaled to RL.

5. Results and Accomplishments

5.1 Site Selection

In consultation with Robert Gisiner of ONR and Frank V. Stone of CNO N45, the AUTEC and the ESWTR were selected as the two ranges of highest priority for the proposed research. One of the most critical criteria for this field work involved finding sites where experienced biologists had been working with the species of interest. For the ESWTR, a program was developed involving surveys for cetaceans in Onslow Bay. This was performed by expert marine mammal observers from UNCW, who were familiar with the field site and had vessel logistics in place. For the initial field work near AUTEC, the possibility of working with biologists with established field efforts on Abaco Island was explored. Two different groups had conducted several years of field work there. Alessandro Bocconcelli and Peter Tyack conducted an initial scoping trip. While the site appeared promising, it was impossible to develop an agreement between the two groups working there. Given these problems, the plan was altered to find a site in the best place to learn how to tag beaked whales, with the goal of returning to AUTEC once these skills were developed.

Therefore, a global search was undertaken for sites where biologists routinely sighted beaked whales of the genera *Ziphius* or *Mesoplodon* in sites where the weather was predictably calm enough to allow tagging (e.g. Figure 17). A site was identified in the Ligurian sea where *Ziphius* was the fourth most common cetacean sighted by a whale watching group BluWest, which had excellent naturalists on board each cruise. The first beaked whale field work conducted as part of the SERDP grant involved an initial research cruise at a site where field biologists had successfully been working with beaked whales in the Ligurian Sea between Italy and France. The weather was predictably good for tagging during the right season, and *Ziphius* was regularly sighted in a specific site. A close collaboration was formed with the Italian team and the groups worked together very well.

For the second year of field work in 2002, a cruise was conducted at the AUTEC range to see how helpful the range arrays would be for putting the tagging vessel on whales. The focus of this work was to determine how difficult it was to find beaked whales, and if possible, to tag them. However, since these species had never been tagged before, there also was a goal of finding and tagging other odontocete species on the range. During this effort, the tagging team was able to tag 3 pilot whales (*Globicephala macrorhynchus*), one melon headed whale (*Peponocephala electra*), and one rough toothed dolphin (*Steno bredanensis*). However, our ignorance of the vocalizations of beaked whales at this point hindered use of the range arrays for finding beaked whales, a main focus of this work. The visual observers were able to sight one group of 7 *Mesoplodon* and one single individual, but the acoustic monitors were unable to help the vessels find this genus.

Figure 17. Observation vessel watching surfacing *Mesoplodon densirostris* with cliffs of El Hierro visible in background. Photo Credit: WHOI. Fieldwork was supported by University of La Laguna and Governments of El Hierro and the Canary Islands. Research was conducted under US NMFS permits no. 981-1578-02 and 981-1707-00 and a permit from the government of the Canary Islands.

5.2 First Tagging of a Beaked Whale

In October 2002, during the second beaked whale cruise in the Ligurian Sea, the field team was able to tag the first *Ziphius cavirostris* ever tagged. Figure 18 illustrates the tagging method. Rather than using the cantilevered 13 m pole, a shorter hand-held pole was used. This functioned better for the smaller, faster moving beaked whales, which spend shorter periods of time at the surface. This tag lasted for about 20 minutes as can be seen in the depth record in Figure 19.

Figure 18. First tag attached to a Cuvier's beaked whale, *Ziphius cavirostris*, Ligurian Sea, October 2002. Photo Credit: Patrick Miller. Research conducted under US NMFS Permit no. 981-1578-02

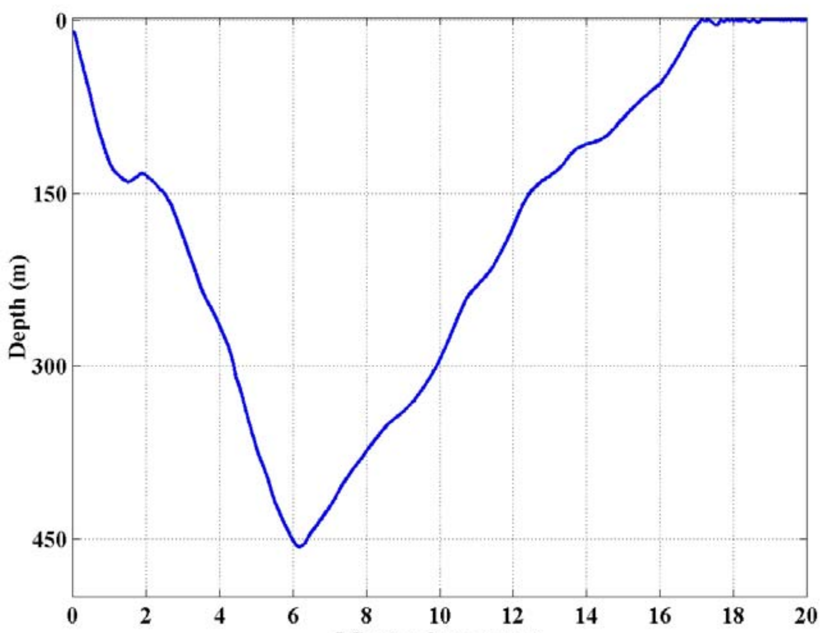


Figure 19. Depth profile from the first attachment of a tag to a Cuvier's beaked whale, *Ziphius cavirostris*, October 2002.

5.3 DTAG Redesign

This first version of the DTAG had a hydrodynamic form, but was relatively high off the back of the whale. For a maneuverable animal such as a beaked whale, it was believed that the early release during the short 20 minute attachment was caused by high drag when the whale rolled. Therefore, as part of this SERDP project, the electronics and attachment of the DTAG was redesigned for better attachment to beaked whales.

The main goals in redesigning the DTAG were to halve its weight and volume while improving its storage capacity and recording fidelity. An additional concern was to improve the pressure tolerance of the design as pressure tests of the original DTAG indicated the potential for failure at depths beyond 1200m, a depth considered attainable by beaked whales. Taking advantage of recent improvements in component density and performance, an electronics module was produced in early 2003 that fully met these goals. A number of key design features ensured the success of the new system. The pressure failure of the original DTAG electronics module, which comprised a stack of circuit boards potted in epoxy resin, was traced to a mismatch between the bulk moduli of elasticity of the fiberglass circuit boards and the encapsulant. This mismatch led to buckling of the boards at high pressure, unseating components. For the new design, the circuit boards were protected with an acrylic housing and then the entire module was sealed inside a flexible oil-filled bag. By avoiding a rigid encapsulant, the pressure failure mode was eliminated and the new tag operated perfectly in pressure tests to 2000m water depth. The oil-filled bag design conveys two other advantages. First, the tag electronics can be serviced easily by removing the tag from the bag, a feature not available with a rigid encapsulant. Secondly, tag components requiring a flexible mechanical housing can be included inside the bag. Specifically, the pressure transducer, the hydrophone, and the rechargeable battery, all of which were externally mounted in the original DTAG, were integrated into the electronics module in the new design. The result was a completely self-contained device, shown in Figure 20. After some trial and error, a high strength, flexible polyurethane material for the bags was selected and these are now custom molded at low cost. The acrylic internal housing for the tag is milled using a computer numerical control (CNC) mill. The resulting module is extremely rugged and significantly cheaper to produce than was the original tag.

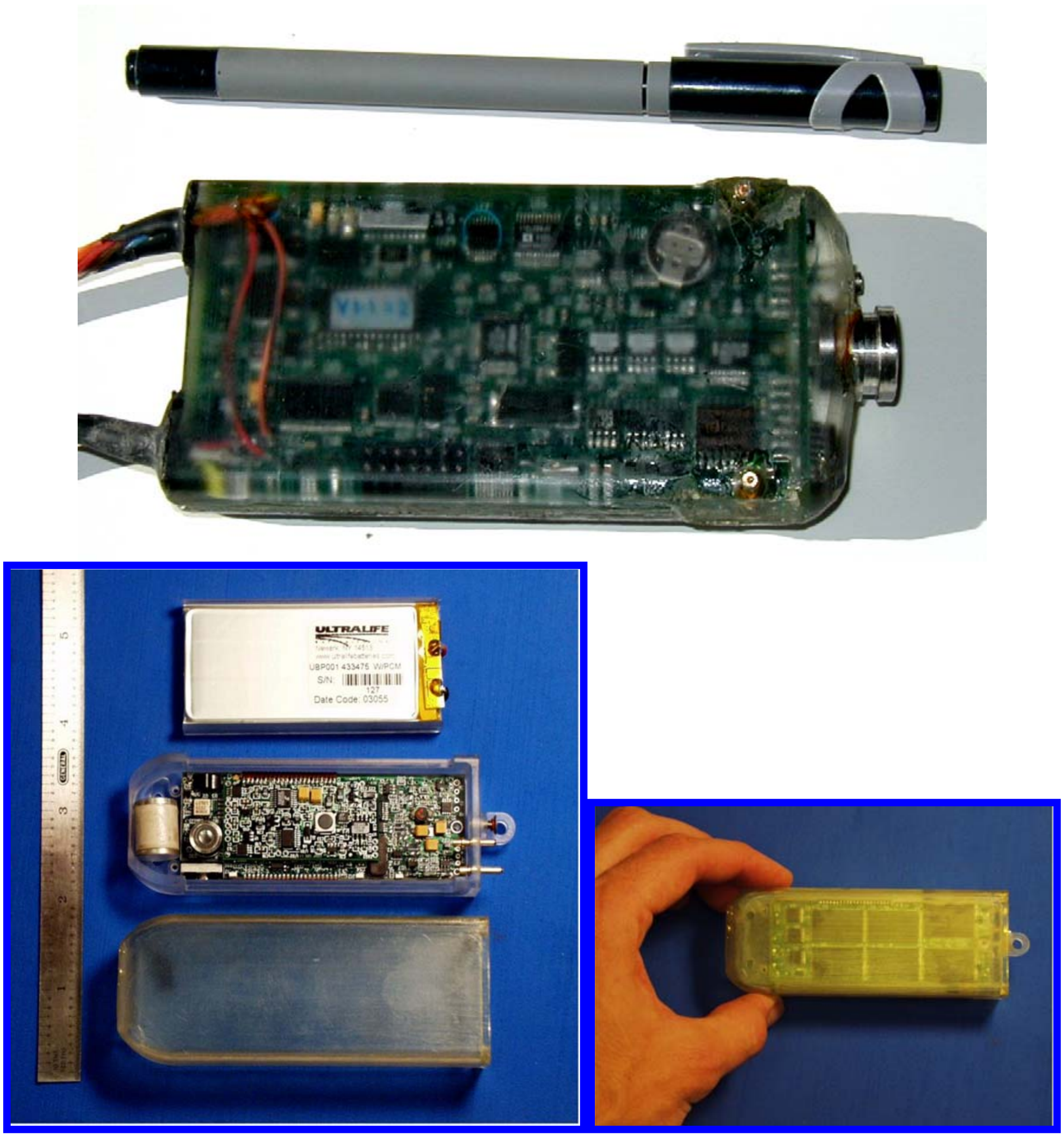


Figure. 20. Above: the original DTAGV1 electronics module encapsulated in epoxy resin. The wires on the left side of the figure go to a battery module and a hydrophone. Lower: the new DTAGV2 electronics module in an oil-filled bag containing also the battery and hydrophone.

Another goal in designing the new tag was to increase its storage capacity and recording fidelity to increase the chance of capturing the possibly weak and high frequency vocalizations of beaked whales. Specifically, it was desired to achieve 16 bit recordings at sampling rates of at least 100 kHz and with recording durations of more than 12 hours implying a memory capacity of nearly 9 GB (Gigabyte) (2 bytes/sample x 100000 samples/second x 12 hours). Since 1999, the density of the FLASH memory devices used in the tag has doubled each year. In 2003, individual chips with 256 MB of memory became available. To meet the size constraint, the new tag contains

only 12 memory chips as compared to 24 in the old design. With the high density parts, this translates into a storage capacity of over 3 GB. Although this capacity compares favorably to the old design DTAG which reached a capacity of 2 GB in 2002, it did not reach the design goal for storage capacity. Since 2001, under SERDP funding, methods for compressing the audio data recorded by the DTAG with the objective of enhancing the effective capacity of the tag has been researched. Industry standard compression strategies such as MP3 were examined and rejected due to the significant artifacts generated by these methods. Instead there was a focus on loss-less audio compression algorithms such as Shorten which guarantee the precise reconstruction of the original data. A version of Shorten which was called X3 tailored to the types of sounds recorded on the DTAG was developed. Evaluation of this algorithm on archived tag data suggested that compression factors of at least 3 would be achieved, i.e., the compressed audio data would require less than 1/3 of the memory of the uncompressed data. This compression factor, combined with the 3 GB capacity of the tag yielded an effective capacity of 9 GB, meeting the design goal. X3 was implemented on the new tag and has been tested exhaustively in field deployments of 5 species of cetaceans. The algorithm routinely provides compression factors of 3.5 at a sampling rate of 96 kHz and is a critical enabling technology from the SERDP program.

With the reduced size and weight of the new tag as compared to the original design, less flotation was required resulting in a smaller overall package. After evaluating a number of tag body designs, a squat design with 4 small suction cups was chosen, (see Figure 21 bottom). A similar design had performed exceptionally well on captive dolphin and belugas. It was hoped that the low profile and stable package would decrease the incidence of tags being rubbed off by conspecifics. It was also hoped that having 4 suction cups would improve the longevity of attachment and the fidelity of the orientation measurements made by the tag. A two-year program of evaluation of suction cup materials and shapes led to the design of a custom silicone suction cup for the new tag. This cup has low stiffness making it easy to deploy and comfortable for the animal, and has extremely low leakage as needed for long attachment durations. The pure silicone used in the cup has density close to water and so contributes little to the overall tag weight in water. The completed tag weighs 0.7 lb (0.32 kg) and occupies less than one half of the volume of the original DTAG. With this light weight, the tag is straightforward to deploy from both cantilevered pole and hand pole.

The top half of Figure 21 shows complete attachment package for the DTAGV1 and the bottom half shows the new redesigned attachment package for the DTAGV2. Figure 22 shows a DTAGV2 on a surfacing beaked whale, illustrating the low profile of the redesigned tag on the whale.

Figure 21. Top: DTAGV1 in the housing and suction cups used for attachment. Bottom: DTAGV2 developed with support from SERDP in the housing and suction cups used for attachment.

Figure 22. DTAGV2 on a beaked whale. Photo Credit: Marco Ballardini of BluWest. Research conducted under US NMFS Permit no. 981-1707-00.

5.3.1 Sensing physiological signals on the DTAG

The tag was also able to detect the sounds of heartbeats in *Mesoplodon densirostris*, when the whale was at the surface and not moving rapidly (Figure 23). Like *Ziphius*, *Mesoplodon* ascend slowly from deep dives; their heartbeat is audible during near-surface resting. This kind of data can be extremely useful as a response measure for physiological reactions to sound and other stimuli (Miksis *et al.* 2001). Measuring respiration events in the tag data from beaked whales may also be used to estimate metabolic rate over periods of hours. Unfortunately the only goal set for this project which was not achieved was the development of an electrocardiogram (EKG) sensor to track heart rate throughout the dive.

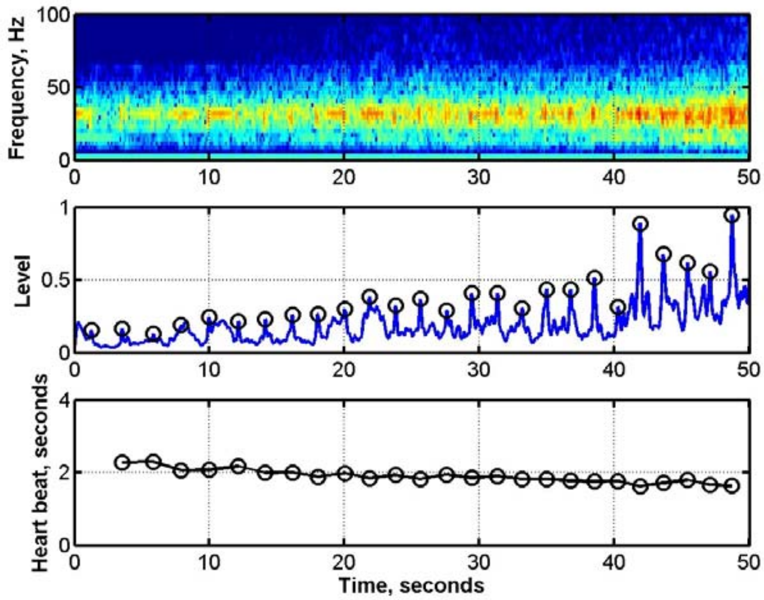


Figure 23. Acoustic detection of heartbeat in DTAGged *Mesoplodon*.

5.4 Initial field work on beaked whales

The first results for the beaked whale component of this project involved establishing field sites where the team could routinely sight beaked whales of the species most commonly reported to strand coincident with naval exercises: *Ziphius cavirostris* (Zc) and *Mesoplodon densirostris* (Md). At the end of the 2002 field season, contrasting the success with tagging in the Ligurian Sea with the difficulties working on beaked whales at AUTEC, the search for field sites was therefore expanded, and a site found in the Canary Islands, where beaked whales are routinely sighted from land (Figure 17). This allows shore observers to direct the tagging vessel towards whales. These shore observers were able to play the role initially planned for the AUTEC passive monitoring, and the lee of the island provided protected waters.

During the first and second years of this SERDP project, major efforts focused on identifying and visiting field sites for beaked whales, and working on methods to attach tags. During the spring of the third year, in response to a nuisance lawsuit, a new Federal permit for research on marine mammals had to be written and applied for. The new permit was received by June 2003, just before the next scheduled field work. Due to considerable effort on the part of the Permit Office of the NMFS Office of Protected Resources, the permitting issues did not delay or impede any field work. During 2003, Peter Tyack worked closely with NMFS on effects of sound on marine mammals and testified three times to Congress on the MMPA.

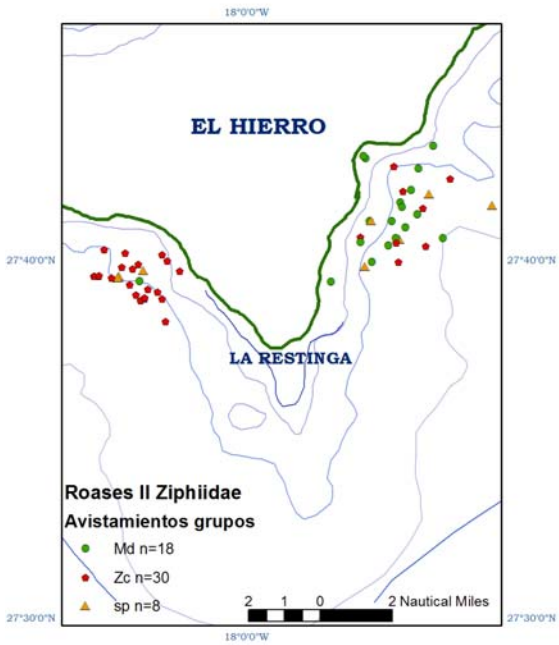
During the fall of 2003, DTAGV2 proved extremely well suited to tagging beaked whales, with attachments lasting 3-34 hours on the two species of most concern for mass stranding, *Ziphius cavirostris* and *Mesoplodon densirostris*. Data from the tagged whales could be used to define their vocal behavior, with clicks produced primarily below 500 m. They may dive for 85 min to nearly 2000 m depth, and show an echolocation pattern when foraging that is similar to sperm whales. Details of the initial results from tagging beaked whales are presented in Johnson et al.

(2004) and Madsen et al. (2005). Both the dive and vocal data are critical for understanding risk factors for beaked whales and mid-frequency sonars. Digital recordings of beaked whale click sounds were distributed to NUWC. The team's ability to specify the vocalizations of these beaked whales opened the possibility of developing systems for passive acoustic detection. This is important for monitoring and mitigation of potential impacts of noise on navy ranges and during naval exercises. During all three initial years of this project (2001-2003), visual and acoustic surveys for marine mammals were conducted in Onslow Bay.

5.4.1 Initial Tagging of Beaked Whales in the Ligurian Sea and off the Canary Islands

In March/April of 2003 the first field effort in the Canary Islands, Spain was conducted near the islands of Tenerife and El Hierro in collaboration with biologists from the ULL. No beaked whales were encountered at Tenerife but pilot whales were, and 13 pilot whales were tagged in 7 good weather days, with attachment durations of up to 7 hours. During 8 good weather days at El Hierro, both *Ziphius cavirostris* and *Mesoplodon densirostris* were encountered on all but one day. Follows of up to 2 hours were possible, but after many tagging attempts, only one touch of the tail stock was achieved.

Working with European partners, ULL in the Canary Islands and BluWest in the Ligurian Sea, two sites were discovered with very high encounter rates that make them ideal for learning how to tag beaked whales, and also developed the ability for sighting, photo-identification, and focal follows of these species. The left panel of Figure 24 shows sightings of both species near the La Restinga peninsula on the island of El Hierro in the Canary Islands. The right panel of Figure 24 shows sightings of *Ziphius* in the Gulf of Genoa in the Ligurian Sea. While the initial goal had been to work on US Navy ranges, both of these sites are very relevant for the sonar/beaked whale issue. Atypical mass strandings of beaked whales coincident with the presence of naval ships have been reported both in the Canary Islands (Fernandez et al. 2005; Simmonds & Lopez-Jurado 1991) and the Ligurian Sea (Anonymous 1963a; Anonymous 1963b).



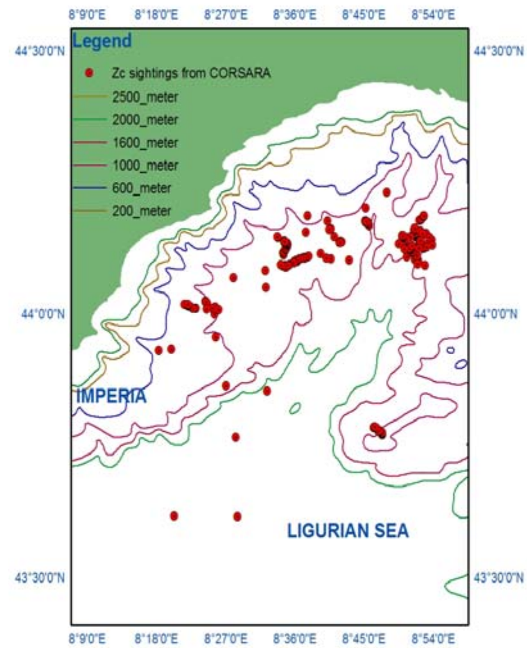


Figure 24. Sightings of Cuvier's beaked whales (red dots) and Blainville's beaked whales (green dots) off the island of El Hierro in the Canary Islands (left) and in the Ligurian Sea (right).

One of the surprises to the team was the ability to use traditional techniques of photographing distinctive markings on individual beaked whales. Figure 25 shows photographs taken on two separate occasions of two different individual *Ziphius* in the Ligurian Sea. This work depends upon highly skillful photographers among the field biology team. Resightings of individual whales in each of our two primary beaked whale field sites across different years demonstrates strong site fidelity.

Figure 25. Photo-identification showing repeated sightings of the same individual Cuvier's beaked whales, *Ziphius cavirostris*, on different days (upper row and lower row) in the Ligurian Sea. Photo Credit: Albert Sturlese of BluWest and Federico Famelia. Research conducted under US NMFS Permit no. 981-1578-02.

During September 2003, the tagging team worked again with BluWest in the Ligurian Sea and tagged two *Ziphius cavirostris* in one week with DTAGV2 providing attachment durations of 3 hours and more than 30 hours. The field effort was then moved to the Canary Islands where 3 and 16 hour tag attachments to *Mesoplodon densirostris* were accomplished. While it is time consuming to find the field opportunities for attaching tags to beaked whales, these successes with attachments lasting for the goal durations gave confidence that the engineering problems and field logistics required to conduct routine tagging field work with beaked whales was solved. A main lesson of this project was the need for extended field time for tagging success.

Advances in digital electronics in 2004 allowed the improvement of DTAGV2 with minimal design changes. 512 MB memory chips became available in 2004 allowing tags with 6 GB capacity. This allowed sampling at 192 kHz and/or the use of stereo hydrophones while still meeting the design goal of 12+ hour recordings.

Given the success in tagging beaked whales in the two European field sites, an attempt in the spring of 2004 was made to duplicate this success in the originally proposed site in the Bahamas. During May the team worked with Diane Claridge in Abaco to tag beaked whales. Unfortunately, the weather was unseasonably bad, and there were few opportunities to attempt to tag. The field effort was cut short one week because the forecast was predicted to continue unworkable. During June, with additional funding from the National Oceanographic Partnership

Program (NOPP), field work was done again at the Gulf of Genoa site. This work was extremely successful with 5 whales tagged in 3 weeks. The dive patterns from these animals differed from those from the preceding year, and included dives among the longest (>85 min) and deepest (1950 m) recorded reliably from marine mammals. During this field effort, the team also documented *Ziphius* at the surface for prolonged periods, which rules out a hypothesized risk factor for sonar exposure (that the whales were chronically supersaturated and could not spend more than minutes at the surface). Tags were attached to two beaked whales in rapid succession, providing a long tag record from two whales at the same time. This allowed the team to track the distance between the animals every time one animal vocalized and the sound was detected on the other tag. These data enable estimation of the source level and directionality index of *Ziphius* (Zimmer et al. 2005a), both critical parameters for estimating the probability this species can be detected with passive acoustic monitoring. The stereo high frequency tags were deployed and obtained full bandwidth recordings of ultrasonic clicks. The team was able to measure differences in time of arrival of echoes at the two hydrophones, which enabled estimation of the direction from which the echo came. During September 2004, another field effort was conducted at El Hierro, succeeding in an 18 hour tag attachment for *Mesoplodon*. The problems at the Bahamas site and continued success in Liguria and El Hierro highlighted the importance of our progress in finding and establishing reliable sites for work with beaked whales.

During 2005, the team continued successful tagging efforts in Liguria in June, with tags attached to two *Ziphius*, and in El Hierro in September, with tags attached to 4 *Mesoplodon*. This yielded a total of 7 tagged animals for each species, providing an excellent data set to quantify the diving and vocal behavior in these two sites.

During March of 2006, the team took advantage of a short window when NUWC and the BMMS were monitoring marine mammals at the AUTEC range to attempt to tag. There were two days with adequate weather and the acoustic monitors quickly were able to put the tagging vessel onto beaked whales. The tagging vessel was able to approach the whales several times. The tagging team was unable to tag a whale, but the lack of reaction from the whales suggested that, with the help of the acoustic monitors, AUTEC will be as promising as our European sites for tagging beaked whales. It just requires sufficient field time to have opportunities for tagging.

Table 1. Summary of Field Work Conducted Under this Project

Year	Month	Activity	Collaborators	Location
2001	June	Tagging	BluWest	Ligurian Sea
2001	Several	Surveys	Duke	Onslow Bay, NC
2002	Sept-Oct	Tagging	BluWest	Ligurian Sea
2002	March	Tagging	NUWC, BMMS	AUTEC
2002	Several	Surveys	Duke	Onslow Bay, NC
2003	September	Tagging	BluWest	Ligurian Sea
2003	April	Tagging	ULL	Canary Islands
2003	Several	Surveys	Duke	Onslow Bay, NC
2004	May	Tagging	BMMS	Abaco Island
2004	June	Tagging	BluWest	Ligurian Sea
2004	September	Tagging	ULL	Canary Islands

2005	June	Tagging	BluWest	Ligurian Sea
2005	Sept	Tagging	ULL	Canaries
2005	Sept-Oct	Survey	BMMS	AUTEC
2006	March	Tagging	BMMS	AUTEC

Table 2. DTAG Data Sets for Beaked Whales 2002-2005

Date	ID	Tag id	Record time / carry time (hours)	# of full deep dives	Sampling Rate, kHz			
Roases IV, El Hierro, September 2005								
10/21/05	md294a	214	2.9	1	192[s]	-		
10/21/05	md294b	212	7.7	3	192[s]	-		
10/12/05	md285a	214	17.4 / 18+	7	192[s]	released		
10/04/05	md277a	212	6.7	2	192[s]	-		
Total	4 tags		34.7 hours	13 dives		8.7 hrs ave. tag		
Zifios VI, Liguria, June 2005								
6/16/05	zc167a	214	7.5	3	192[s]	-		
6/19/05	zc170a	212	11.8	6	192[s]	-		
Total	2 tags		19.3 hours	9 dives		9.7 hrs ave. tag		
Roases III, El Hierro, September 2004								
10/13/04	md287a	212	18.3	9	192[s]	released		
Total	1 tag		18.3 hours	9 dives		18.3 hrs ave. tag		
Zifios IV, Liguria, June 2004								
6/08/04	zc160a	207	5.6	2	96	-		
6/09/04	zc161a	203	8.9	4	96	-		
6/09/04	zc161b	204	15.8 / 18.8	8	96	released		
6/23/04	zc175a	212	7.5 / 14.0	3	192[s]	released		
6/27/04	zc179a	212	3.8	2	192[s]	-		
Total	5 tags		41.6 hours	19 dives		8.3 hrs ave. tag		
Roases II, El Hierro, October 2003								
10/11/03	md284a	207	15.4 / 17.0	5	96	released		
10/25/03	md298a	204	3.0	2	96	-		
Total	2 tags		18.4 hours	7 dives		9.2 hrs ave. tag		
Zifios III, Liguria, September 2003								
9/17/03	zc260a	204	3.0	1	96	-		
9/20/03	zc263a	204	15.6 / 34+	8	96	released		
Total	2 tags		18.6 hours	9 dives		9.3 hrs ave. tag		
Zifios II, Liguria, October 2002								
10/02/02	zc275a	11	0.3	0	32	-		
Total	1 tag		0.3 hours	0 dives		0.3 hrs ave. tag		

[s] Stereo recording

5.4.2 Onslow Bay Surveys

Surveys for marine mammals were conducted from 2001-2003 at Onslow Bay near the planned site of the ESWTR. The overall objective of this project was to document seasonal patterns of residency of delphinid species in the inshore and mid-shore waters (10-35 m depth) of Onslow Bay, North Carolina (NC), and to assess the value of acoustic monitoring as a supplement to photo-identification. The methods included the following:

- Conduct monthly photo-identification and acoustic monitoring surveys
- Compare dorsal fin images of bottlenose dolphins to regional photo-identification catalogs
- Compare dorsal fin images of spotted dolphins to first catalog of spotted dolphins for western mid-Atlantic
- Explore ecological determinants of distribution for both species (bathymetry, bottom type, sea surface temperature (SST))
- Analyze acoustic recordings to document occurrence of vocalizations and distinguish among the species observed

These surveys included counts of animals sighted of each species, photographs to identify individually distinctive patterns of natural markings, and recordings of underwater vocalizations.

Figure 26 shows the location of the survey tracks along with sightings of spotted dolphins, and bottlenose dolphins.

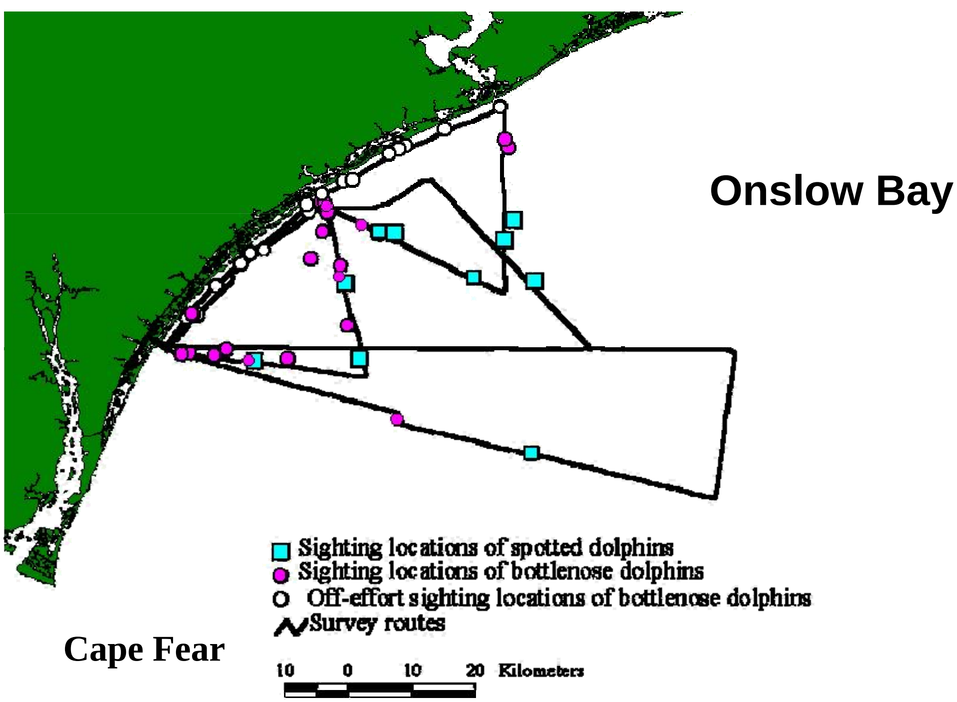


Figure 26. Survey routes and locations of sightings for Onslow Bay Surveys.

Table 3. Marine Mammal Surveys at Onslow Bay, NC.

Date	Platform	Field hours	Tracklines (nm)	Bottlenose dolphin Sightings *(Tursiops truncatus)*	Spotted dolphin Sightings *(Stenella frontalis)*
23-Apr-01	SEAHAWK	6.5	95.0	2	1
24-May-01	SEAHAWK	8.0	120.0	2	1
28-Jun-01	SEAHAWK	7.0	107.0	1	4
17-Aug-01	SEAHAWK	5.5	97.7	1 (off effort)	0
27-Sep-01	SEAHAWK	6.0	99.3	2	0
24-Oct-01	SEAHAWK	7.0	105.0	4	0
17-Jan-02	CAPE FEAR	7.0	102.0	1	1
19-Feb-02	SEAHAWK II	7.0	98.0	3	0
25-Feb-02	CAPE FEAR	5.5	n/a	1	0
15-Mar-02	SEAHAWK II	5.5	95.8	1	0
17-Apr-02	SEAHAWK II	6.3	102.0	0	1
31-May-02	SEAHAWK II	4.5	114.0	4	0
24-Jun-02	SEAHAWK II	7.3	100.0	2	1
8-Jul-02	SEAHAWK II	6.0	97.4	0	1
13-Aug-02	SEAHAWK II	5.3	95.7	0	0
19-Sep-02	SEAHAWK II	5.2	95.8	1 (off effort)	0
20-Nov-02	SEAHAWK II	5.5	95.6	0	0
28-Jan-03	SEAHAWK II	5.0	96.0	0	0
19-Feb-03	SEAHAWK II	5.0	95.9	0	0
16-Apr-03	SEAHAWK II	6.5	101.0	1	2
23-Jun-03	SEAHAWK II	5.5	97.0	0	0
13-Aug-03	SEAHAWK II	5.5	105.0	1	0
16-Oct-03	SEAHAWK II	6.5	100.0	3	0

Figure 27 shows that there was a clear seasonal trend in sightings. For both species, sightings were more common in spring and for bottlenose dolphins sightings were also more common in fall. The seawater temperatures were intermediate for this area during both the spring and fall periods of elevated sightings. In spite of the longer period during which bottlenose dolphins were sighted, the photo-identification suggests that the spotted dolphins represent a small population that is seasonally resident, while the bottlenose dolphins are part of a larger migratory population. None of the 32 bottlenose dolphins photo-identified in Onslow Bay were resighted as part of these surveys, but two matched animals photographed in Murrell's Inlet South Carolina (SC), two in Beaufort NC, and one in Wilmington NC. By contrast, of the 32 spotted dolphins photo-identified, 8 were resighted during the surveys. This very high resighting rate, suggests that a reasonably large percentage of the spotted dolphin population was identified in the surveys.

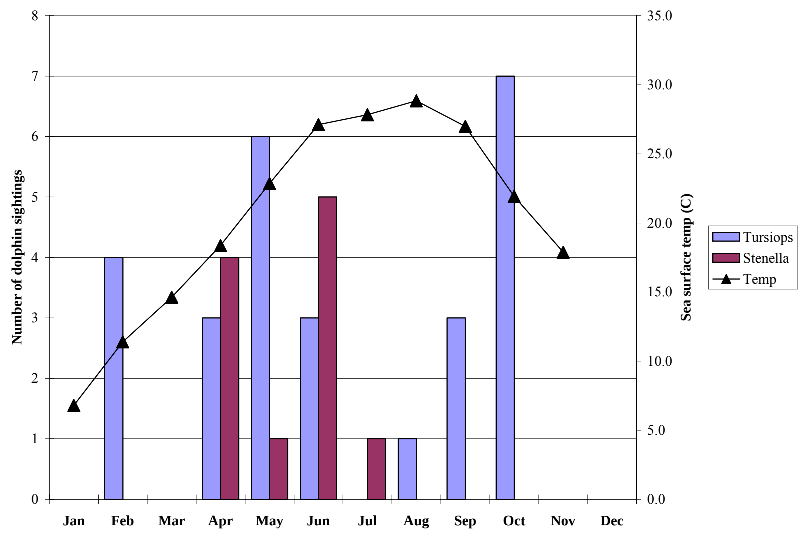


Figure 27. Seasonality of dolphin sightings in Onslow Bay

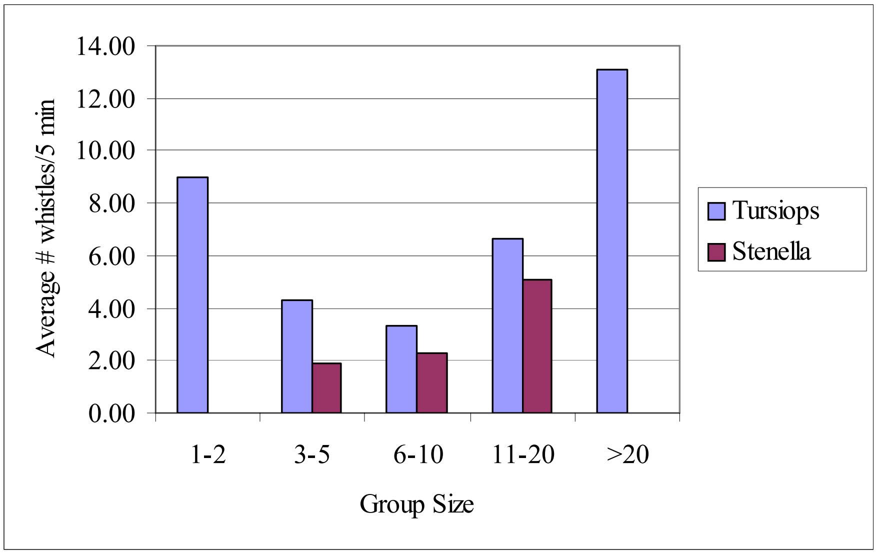
Table 4 demonstrates that the two different species were sighted in different group sizes and in different water depths.

Table 4. Comparison of group size, water temperature and depth for bottlenose and spotted dolphins

	Bottlenose dolphins	Spotted dolphins
***Mean group size**	**21.5**	**7.9**
SD	22.8	4.1
Range	2-75	3-15
Mean temp	**20.8**	**23.7**
SD	5.1	4.3
Range	11.1-28.8	17.4-28.8
***Mean depth**	**14.1**	**18.4**
SD	2.4	2.1
Range	6.7-19.6	14.8-21.9

* (p<0.05)

Recordings of underwater sound were made each time a group was sighted, in order to sample vocalizations. Figure 28 demonstrates that there was a clear trend for vocalization rate to increase with group size. These results suggest that the rates of production of whistles and echolocation clicks are high enough that these animals are good candidates for passive acoustic localization.



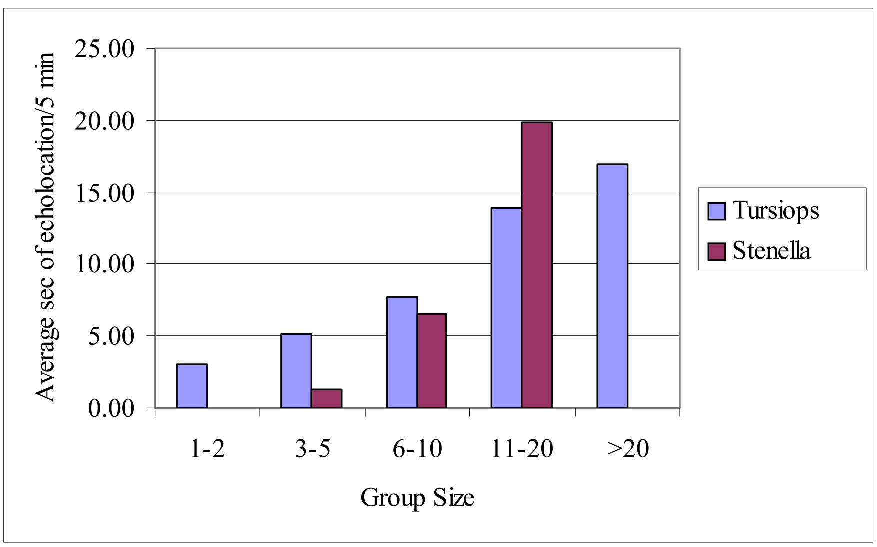


Figure 28. Vocalization Rates of Bottlenose and Spotted Dolphins during Onslow Bay Survey Sightings as function of group size (April 2001 to April 2003). Upper: average number of whistles in a 5 minute period; Lower: average duration of vocalizations.

5.5 Tag Data from Beaked Whales

5.5.1 Dive Behavior of Tagged Beaked Whales

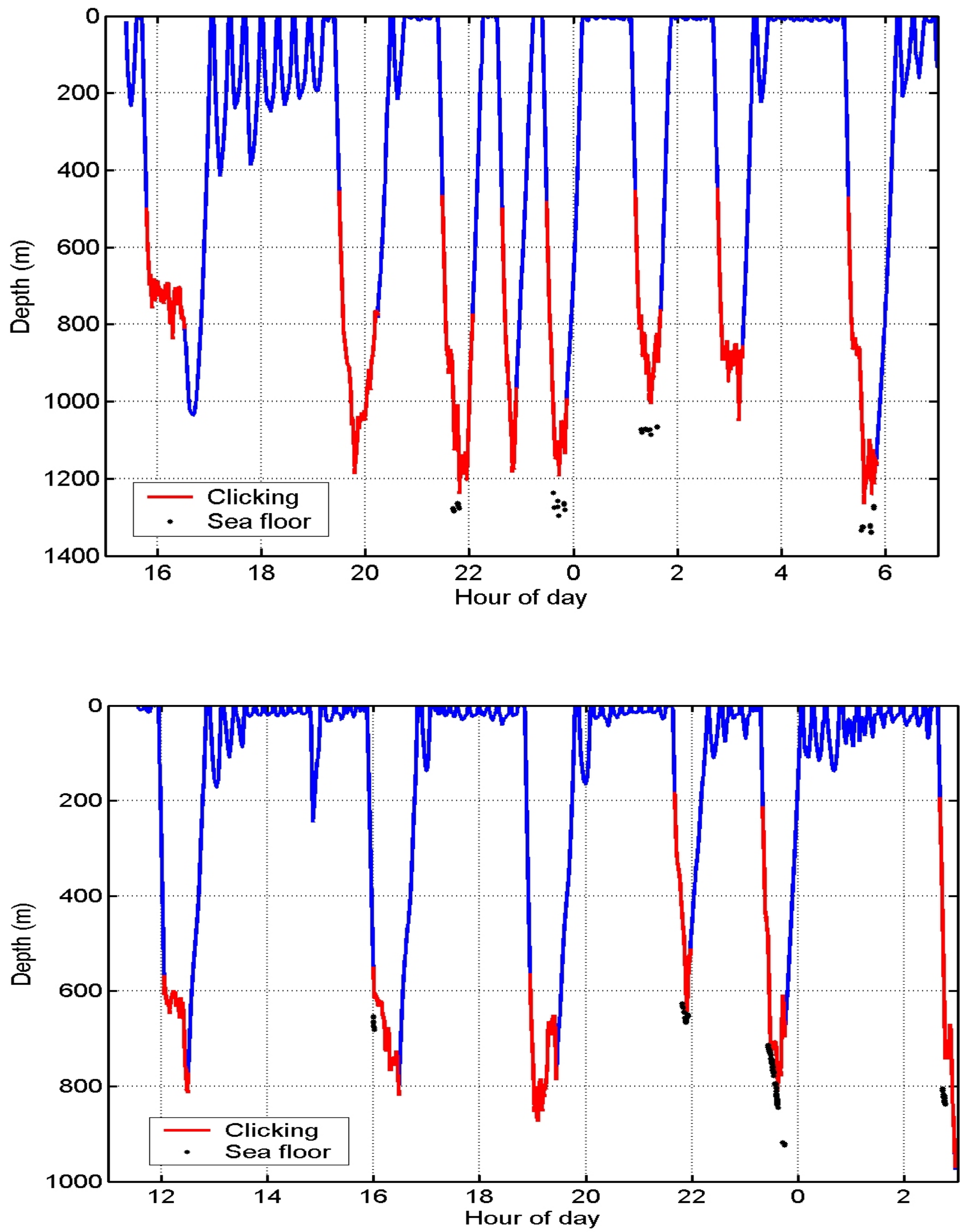


Figure 29. Dive profiles of *Ziphius cavirostris* (top) and *Mesoplodon densirostris* (bottom) from DTAG data. The black dots show the distance from whale to the sea floor measured by the delay time of echoes detected from the clicking whale.

The tag data clearly show the extreme diving behavior of *Ziphius cavirostris* and *Mesoplodon densirostris*. Dives to depths of 1888 m and with durations up to 85 minutes were recorded (Tyack et al. 2006). An example dive profile is shown for *Ziphius* in the upper panel of Figure 29 and for *Mesoplodon* in the lower panel, comprising multiple, deep foraging dives (DFDs) and a number of shorter shallow dives. The blue sections of the dive profiles represent silent portions of the dive; the red sections indicate periods where the tagged whale produced regular echolocation clicks. No vocalizations were detected from the tagged beaked whales when they were within 200 m of the surface, but they all clicked continuously at depth. The *Ziphius* started clicking at an average depth of 457 m and stopped clicking when they started their ascent at an average depth of 856 m (Tyack et al. 2006). The *Mesoplodon* started clicking on descent at an average depth of 426 m and stopped clicking at the start of the ascent at an average depth of 738 m (Tyack et al. 2006). Tagged whales produced regular click trains often punctuated by a brief pause or rapidly accelerating series of clicks, called a buzz. Figure 30 illustrates on the top panel a waveform from the acoustic record of a tagged *Mesoplodon*, showing the transition from regular clicks to a buzz. The intervals between regular clicks for *Ziphius* were close to 0.4 sec (Figure 31). The tagged *Mesoplodon* had a broader range of inter-click-intervals (ICIs), between 0.2-0.4 sec for regular clicks (Figure 31). The ICIs for *Mesoplodon* had a pattern of slow increase or decrease from regular click to click, while the *Ziphius* regular clicks showed little variation around the mean of 0.4 sec.

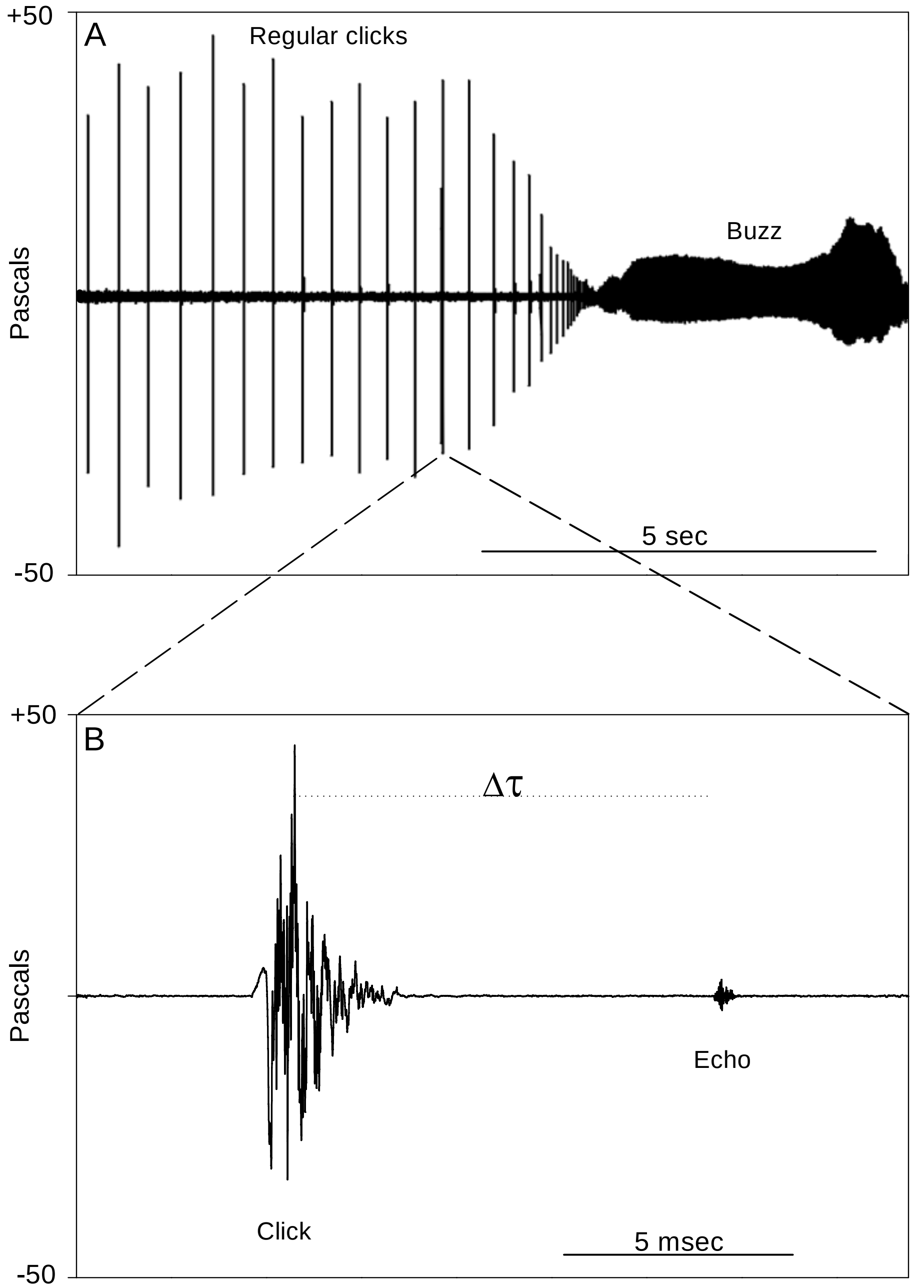


Figure 30. Top: Waveform of clicks as recorded from a DTAG on a *Mesoplodon*. Bottom: blow up of one regular click showing echo. (Figure 2 from Madsen et al. 2005).

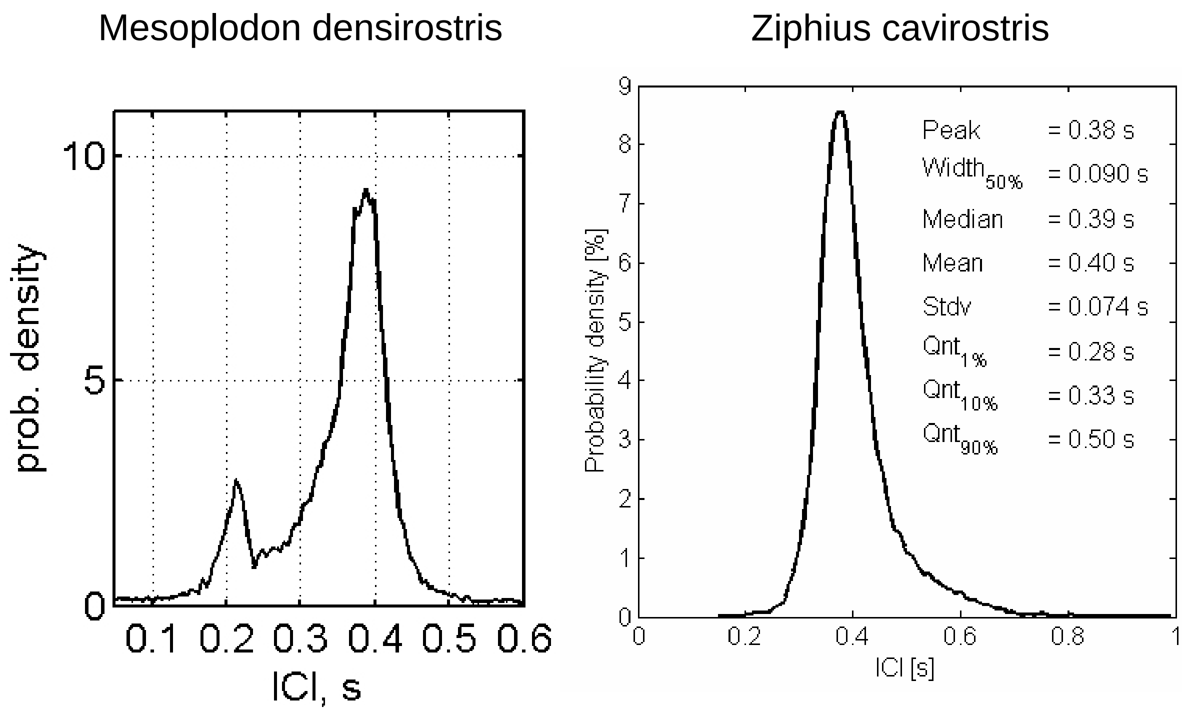


Figure 31. Plots of the probability density for regular clicks in *Mesoplodon* (left) and *Ziphius* (right).

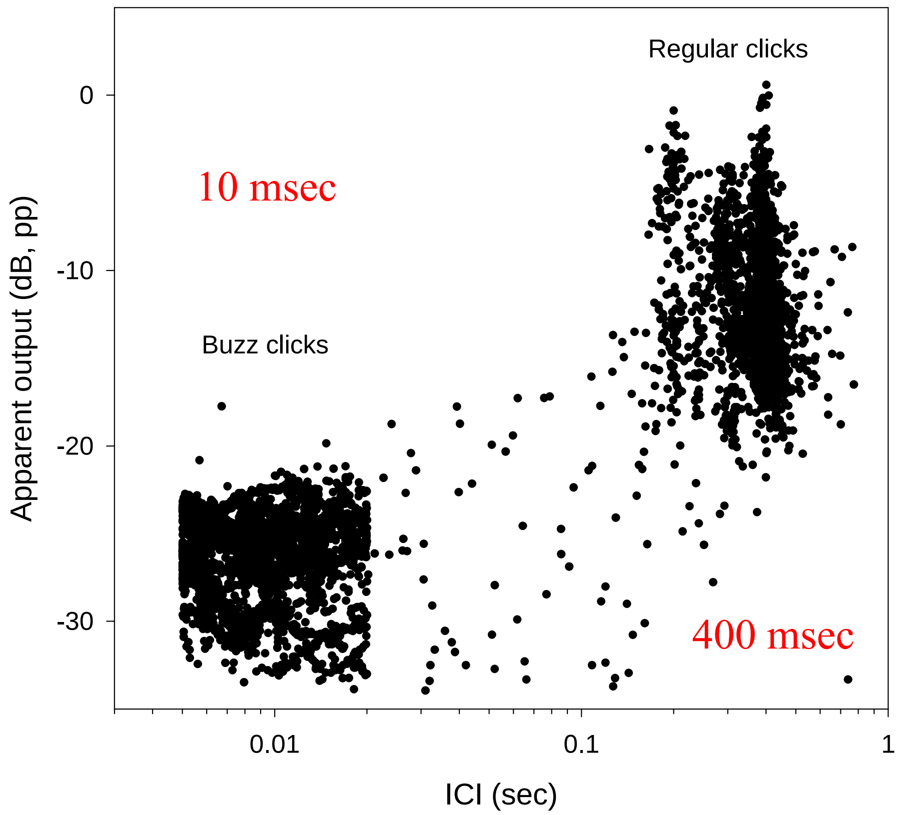


Figure 32. Inter-Click-Interval (ICI) vs relative level of a random sample of clicks recorded during foraging dives of two *Mesoplodon densirostris* tagged in the Canary Islands. (Figure 3 from Madsen et al. 2005).

Figure 32 illustrates the bimodal nature of the ICIs of *Mesoplodon* clicks. There are two distinct patterns of ICI: regular clicks averaging 0.2-0.4 sec ICI, and buzz clicks with shorter ICIs ranging from 0.005-0.020 sec. For each foraging dive, the whale produces about 10,000 buzz clicks and about 2500-5000 regular clicks. The trains of regular clicks end in a sudden increase in click rate, up to about 200 clicks/sec for both species. This acceleration is called a "buzz", in parallel with the terminology used for other odontocetes and for bats as they close on prey (Miller et al. 1995, Au 1993, Griffin 1958). The interpretation that the buzz represents an attempt to capture prey is reinforced by the observation of echoes from targets in the water column detectable in the regular clicks from all of the tagged whales recorded just before the buzz. The lower panel of Figure 30 blows up the waveform of a regular click recorded just before the transition to a buzz. An echo is clearly visible about 8 msec (millisecond) after the click.

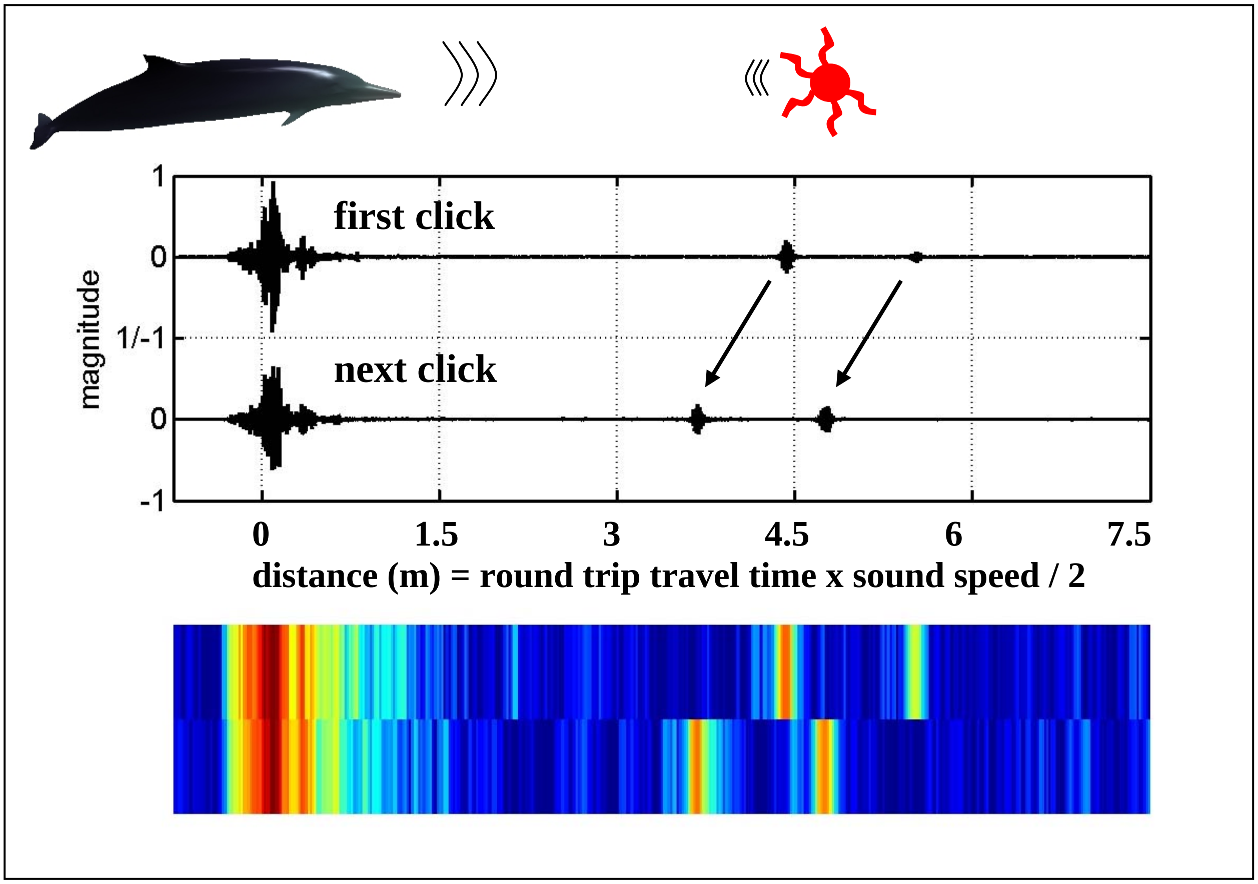


Figure 33. Illustration of colorized sonar echogram for beaked whale clicks.

Figure 33 illustrates the construction of an echogram to visualize echoes from a series of clicks. On the top of Figure 33, two waveforms represent two successive clicks that are time aligned at x=0. Echoes are visible on the top waveform at round trip travel times corresponding to distances of 4.5 and 5.5 m. The echoes in the lower waveform look closer than those on top. The interpretation of the two echoes decreasing in range from one click to the next in the middle plot corresponds to the whale swimming nearer to two relatively stationary targets. In order to stack echoes from more clicks, the intensity of the echo is colorized from red (strong) to blue (weak).

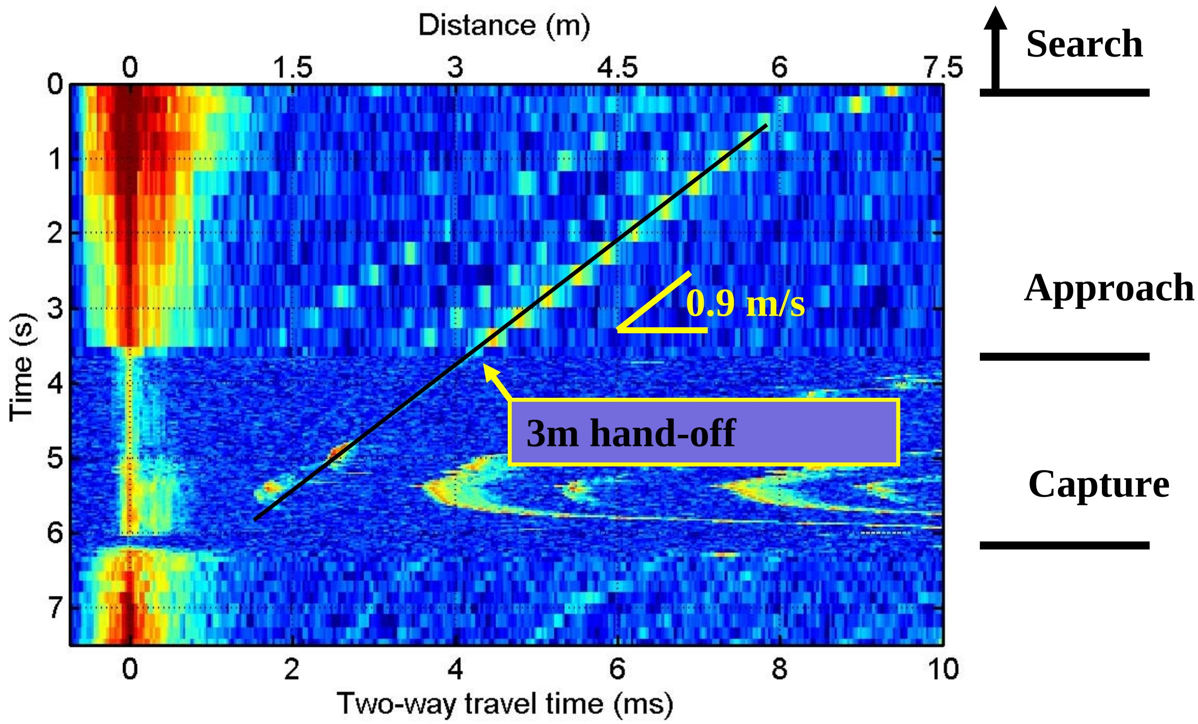


Figure 34. Sonar echogram illustrating prey echoes from clicks of a foraging *Mesoplodon*.

Figure 34 shows prey echoes at ranges between a tagged *Mesoplodon* and the targets from 7.5 m down to 3 m during the last few seconds before a buzz and then down to 1.5 m during the buzz. Figure 34 aligns successive clicks of the tagged whale at X=0 and at the appropriate time on the y-axis. The x-axis indicates the time elapsed between the outgoing click and the returning echo expressed as distance to the target, assuming a sound speed of 1500 m/sec. The color scale indicates strength of the signal (with red=intense to blue=faint). Several different echoes are visible at ranges of 4.5-7.5 m at the upper right side of Figure 34 but by 3.5 sec just before the start of the buzz, one target predominates. The whale switches from regular clicking to a buzz at a range of 3 m at x=-3.5 sec. The slope of the echo line corresponds to a closing rate of 0.9 m/sec. The repetition rate is rapid enough during the buzz, that one can see energy from subsequent clicks on Figure 34 after about 4 sec, starting at a delay corresponding to a range of 7.5 m. Often, echoes from the target cannot be seen during the beginning of the buzz, but the end of the buzz is typically marked by strong echoes closing to < 1 m. This is visible as a sudden strong echo starting at about 5 sec with a delay corresponding to 2 m target range. The end of the buzz is also marked by an increase in the dynamic acceleration of the tagged whale, suggesting a sudden movement to capture the prey. This interpretation is supported by the impact sounds at the end of 65% of buzzes recorded from *Mesoplodon.* Impact sounds were less frequently recorded from the tagged *Ziphius*. Regular clicking resumes soon after the end of the buzz (Figure 34 just after 6 sec). The average number of buzzes recorded per foraging dive was 30 for *Ziphius* and 29 for *Mesoplodon* (Tyack et al. 2006).

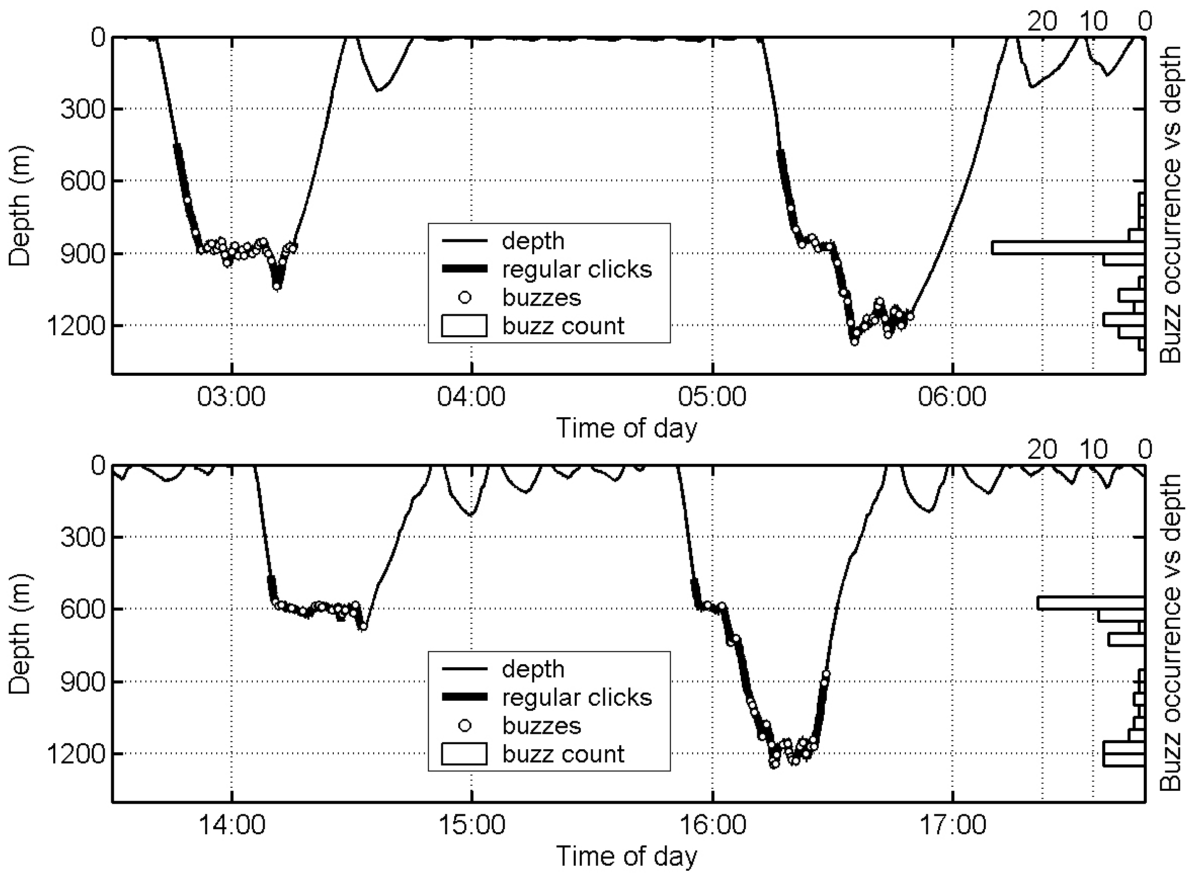


Figure 35. Dive profiles from *Ziphius* (top) and *Mesoplodon* (bottom) indicating regular clicking by a thick line, buzzes by open circles, and tallying buzzes by depth on the right y-axis. (Figure 1 from Tyack et al. 2006)

It is not known if prey are caught during every buzz, but the echo data suggest that buzzes are a good proxy for attempts to capture prey. This interpretation suggests the following view of Figure 35. Beaked whales start producing echolocation clicks at a depth above the first layer where they may feed. They often spend most of the deep foraging dive feeding on one layer (e.g. first deep dive) but may also search for food using regular echolocation clicks interspersed with attempts to feed, as indicated by buzzes. The dive data from *Mesoplodon densirostris* also demonstrate foraging at the bottom on steep canyon walls (Figure 29; note how close the *Mesoplodon* is diving to the bottom as judged by bottom echoes). The dives shown are the 7th and 8th for Zc03_263a and the 3rd and 4th for Md04_287a. All dives deeper than 500 m were found to contain long sequences of echolocation clicks. Johnson et al. (2004) and Madsen et al. (2005) and Tyack et al. (2006) defined these as deep foraging dives. In comparison, dives shallower than 500 m were apparently silent excluding a few isolated sounds. The separation of these two classes of dives is apparent in the scatter plots shown in the left column of Figure 36 in which dive duration is plotted against maximum depth for all dives recorded from *Ziphius* (top) and *Mesoplodon* (bottom). A gap in dive depths between 450 and 700 m coincides with the break point between silent shallow and deep vocal dives.

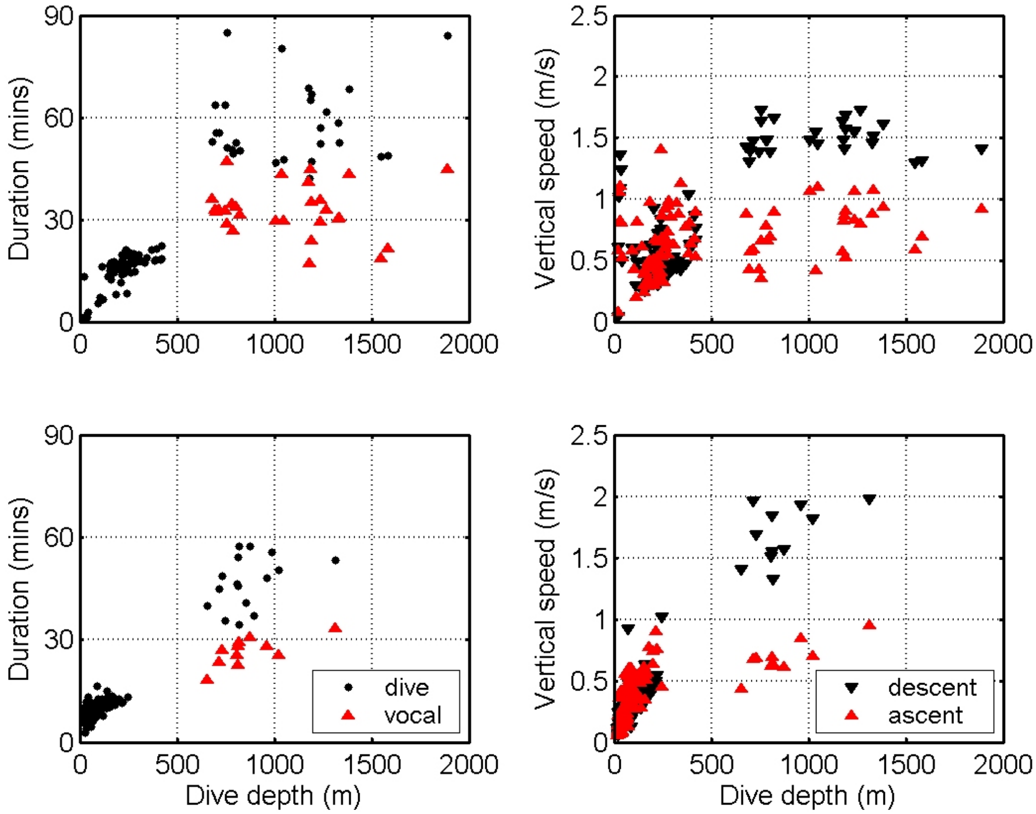


Figure 36: Scatter plots of dive duration (left) and vertical speed (right) as functions of dive depth for all dives deeper than 20 m recorded on *Ziphius* (upper panels) and *Mesoplodon* (lower panels). (Figure 2 from Tyack et al. 2006)

In Figure 36, the left-hand plots show the surface-to-surface dive duration (dots) and the interval from the start to the end of regular clicking (red triangles) in each dive. The absence of dive depths between 500 - 600 m for both species and the observation that only dives deeper than 600 m have consistent vocalizations lead the team to define these as deep foraging dives (DFD). The right-hand plots show vertical speed (i.e., depth rate) as a function of dive depth during descents (downwards pointing black triangle) and ascents (upwards pointing red triangle). The difference between descent and ascent rate for DFDs is apparent.

In summary, acoustic behavior shows that beaked whales hunt by echolocation in deep water between 250 and 1900 m, attempting to capture about 30 prey a dive. This food source is so deep that the average foraging dives were deeper (Zc=1070 m, Md=835 m) and longer (Zc=58 min, Md=47 min) than reported for any other air-breathing species. After most deep foraging dives, beaked whales made a series of shallower dives, apparently to recover from an oxygen debt resulting from these dives, which last about twice the estimated aerobic dive limit. The average interval between foraging dives was 63 min for Zc and 92 min for Md. Table 4 summarizes dive statistics for tagged whales.

Table 5. Lists of data from all deployments of DTAGs on beaked whales that included at least one deep foraging dive. (Table 1 from Tyack et al. 2006)

Whale ID	Gender / age (* probable)	Length record (hrs)	# Deep Foraging Dives (DFD)	Length DFD mean (STD) (min)	Depth DFD mean (range) (m)	# SD and depth mean (range) (m)	IDDI (min) mean (STD)	# SD in IDDI median (range)
Zc03_260a	unknown	3.0	1	50.3	824	3, 224 (22-343)	-	-
Zc03_263a	♀ *	15.6	8	55.3 (12.8)	1145 (1005-1266)	12, 231 (24-416)	61.3 (47)	0 (0-7)
Zc04_160a	adult ♂	5.6	2	84.5 (0.5)	1322 (756-1888)	6, 339 (267-420)	72.9	3
Zc04_161a	sub-adult	8.9	4	55.0 (6.4)	937 (697-1548)	13, 209 (30-388)	65.8 (19)	4 (3-4)
Zc04_161b	sub-adult	15.8	8	54.8 (4.9)	1065 (689-1605)	27, 197 (33-425)	56.9 (22)	3 (1-5)
Zc04_175a	adult ♂ *	7.5	3	67.9 (0.8)	1195 (1125-1324)	3, 182 (148-202)	66.4 (32)	1 (0-2)
Zc04_179a	sub-adult	3.8	2	50.8 (0.4)	737 (724-749)	1, 317	98.8	1
Total *Ziphius*		60.2	28	58.0 (11.4)	1070 (689-1888)	65, 221 (22-425)	63.4 (31)	$2^{\S}$ (0-7)
Md03_284a	adult ♂	15.4	5	51.0 (7.7)	777 (640-855)	42, 61 (20-240)	125.1 (46)	9 (4-12)
Md03_289a	sub-adult	3.0	2	47.2 (2.1)	774 (732-816)	4, 176 (142-217)	66.7	4
Md04_287a	adult ♀	18.3	9	43.8 (7.6)	881 (682-1251)	54, 72 (22-210)	76.9 (40)	6 (1-10)
Md05	Not fully analyzed yet							
Md05	Not fully analyzed yet							
Total *Mesoplodon*		36.7	16	46.5 (7.6)	835 (640-1251)	100, 71 (20-240)	92.3 (46)	$6^{\S}$ (1-12)

5.5.2 Echolocation Clicks of Beaked whales

The audio recordings made by the DTAGs on *Ziphius cavirostris* contain regular (approx. 0.4 sec interval) low-level, wide-bandwidth clicks during deep dives similar to those produced by foraging sperm and pilot whales. The time series and corresponding spectrum level for one such click are shown in Figure 37 (the sound pressure level shown is the RL on the tag which was situated midway between head and dorsal fin). There is evidence in the tag data for a stronger forward-directed beam indicating an echolocation function for these clicks. The recording illustrated in Figure 30 is from the tag which is off-axis (Figure 37); in the beam, the clicks are likely to have emphases at higher frequencies.

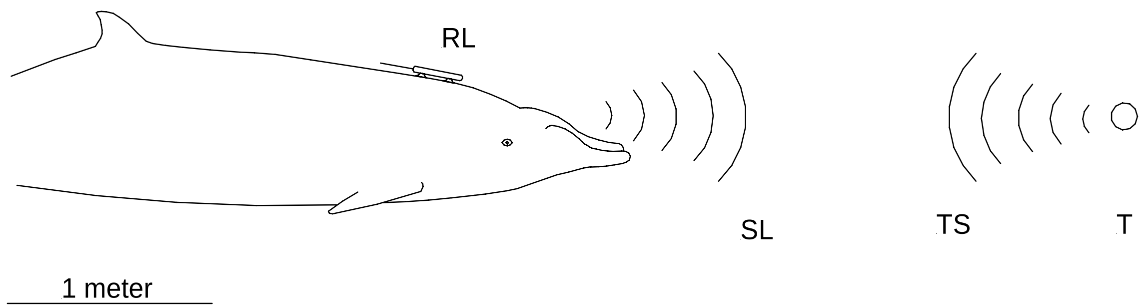


Figure 37: Drawing of position of tag out of the primary beam of the sonar signal.

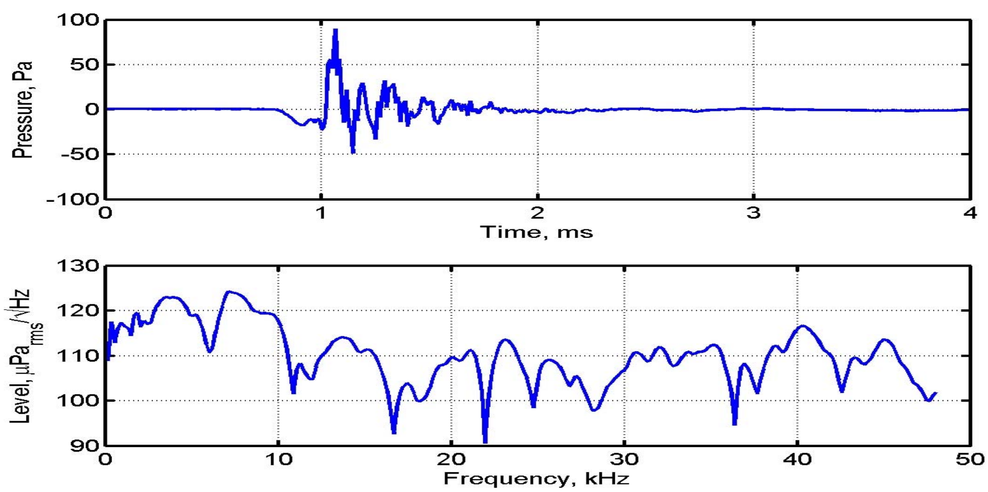


Figure 38: Click recorded from *Ziphius cavirostris* by a DTAG. Upper panel: time series with approximate received level in Pascals (Pa). Lower panel: spectrum level of click showing its wide bandwidth and relatively low intensity. Sampling rate was 96 kHz.

All toothed whales investigated thus far produce directional clicks (Au et al. 1986), which must be measured in the forward beam to characterize their spectrum and level (Møhl et al. 2003). If this were also true for beaked whales, then the clicks recorded on the tag, located well behind the head, would be off the acoustic axis of the tagged whale (Figure 37). However, tags on both *Ziphius* and *Mesoplodon* also recorded clicks that are believed to be from untagged conspecifics for the following reasons:

- The tagged whales were in groups of 2-6 conspecifics that dove synchronously, so other whales were likely to be nearby.
- These other clicks show similar ICIs as the clicks of the tagged whale.
- The other clicks have spectra similar to echoes of clicks from the tagged whale.

The best representation of on-axis clicks in the dataset is believed to come from clicks from untagged conspecifics recorded when they were pointing towards the tagged whale. Click trains that were not from the tagged whale typically varied from low to high to low intensity, with the most powerful clicks having the strongest high frequency component. This kind of pattern would be predicted if a toothed whale were scanning its sonar beam past a receiver (Au et al. 1986). Therefore, selection of clicks with the highest amplitude in a train is assumed to get the best representation of a click in the forward-directed beam (Møhl et al. 2003).

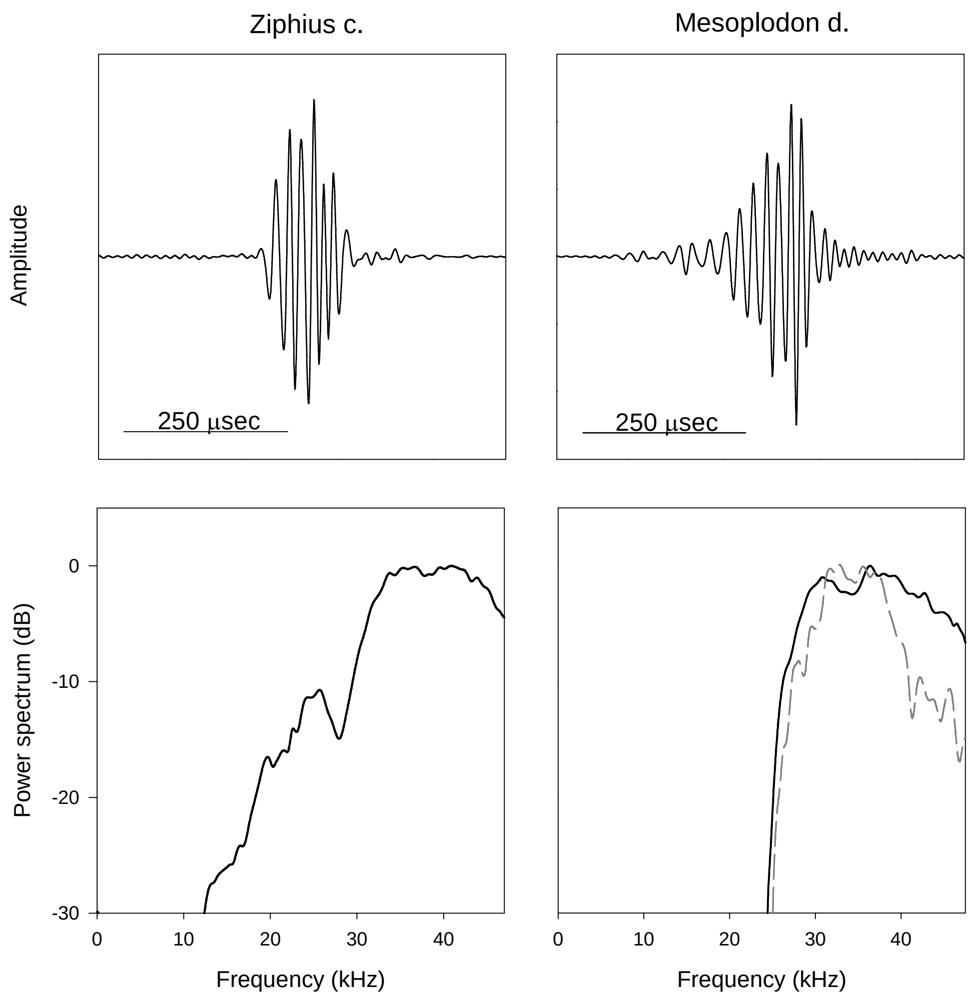


Figure 39. Waveforms and spectra of far-field echolocation clicks from *Ziphius cavirostris* and *Mesoplodon densirostris*. Signals were sampled at 96 kHz and high pass filtered at 1 kHz. Spectra are computed with a 256 point fast fourier transform (FFT) on Hanning windowed data. All spectra are aligned with the spectral peak set to 0 dB. The spectrum indicated by the grey dashed line on the lower right is the bottom echo from the click of a tagged *Mesoplodon*.

Figure 39 illustrates the waveform and spectrum of clicks of *Ziphius* (left) and *Mesoplodon* (right), produced by untagged whales scanning near the tagged whale. These clicks are interpreted to represent examples of clicks recorded in the far field near the axis of the beam. The duration of the on-axis *Ziphius* clicks is about 175 µsec (microsecond), that of *Mesoplodon* about 250 µsec. Off-axis clicks often appear to have a longer duration. Both the *Ziphius* and *Mesoplodon* clicks have a relatively flat spectrum from 30 kHz up to the Nyquist rate of the acoustic sampling (48 kHz). However, the *Mesoplodon* clicks have a much sharper low frequency cutoff, reaching a –20 dB point at 25 kHz vs. 20 kHz for *Ziphius*. There may be some hint of a decrease in spectrum above 40 kHz, but the 96 kHz sampling rate clearly was not sufficient to sample the full frequency range of clicks from either species. These data led the team to recognize a need for an increased sampling rate. Increases in memory density for Flash memory chips made it possible to increase the sample rate of the DTAG to 192 kHz, yielding fuller spectral representation of the clicks as seen in Figure 40.

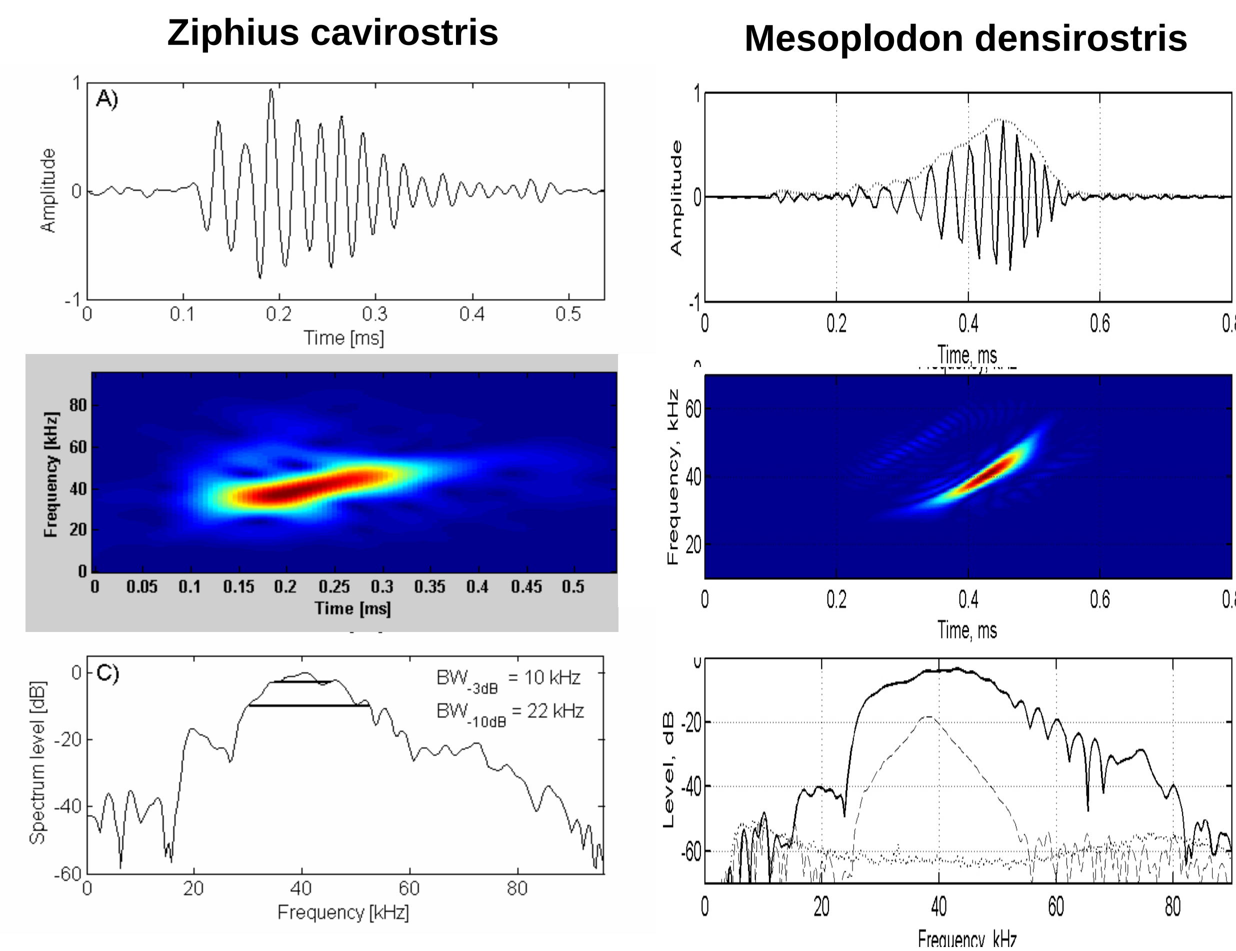


Figure 40. Waveform (top), spectrogram (middle), and spectrum for regular clicks of *Ziphius* (left) and *Mesoplodon* (right). Sampling rate was 192 kHz.

Click sounds have been previously reported for *Ziphius* (Frantzis et al. 2002) and members of the genus *Mesoplodon* (Caldwell and Caldwell 1971, Lynne and Reiss 1992, Marten 2000). None of

the clicks previously reported for *Mesoplodon densirostris* (Caldwell and Caldwell 1971) or *Mesoplodon carlhubbsi* (Lynne and Reiss 1992, Marten 2000) are similar to those reported here, but one of the *Mesoplodon* tags did record some faint signals similar to those described for *Mesoplodon* by Lynne and Reiss (1992) and Marten (2000). While the inter-click-intervals reported for *Ziphius* were similar to the results reported here, the duration and spectra of the clicks differed. One reason for this difference may stem from the limitation in the earlier recording to frequencies below 22 kHz, well below the main frequencies reported here. The initial DTAG recordings did not capture the full bandwidth of beaked whale clicks until the increase in sample rate to 192 kHz.

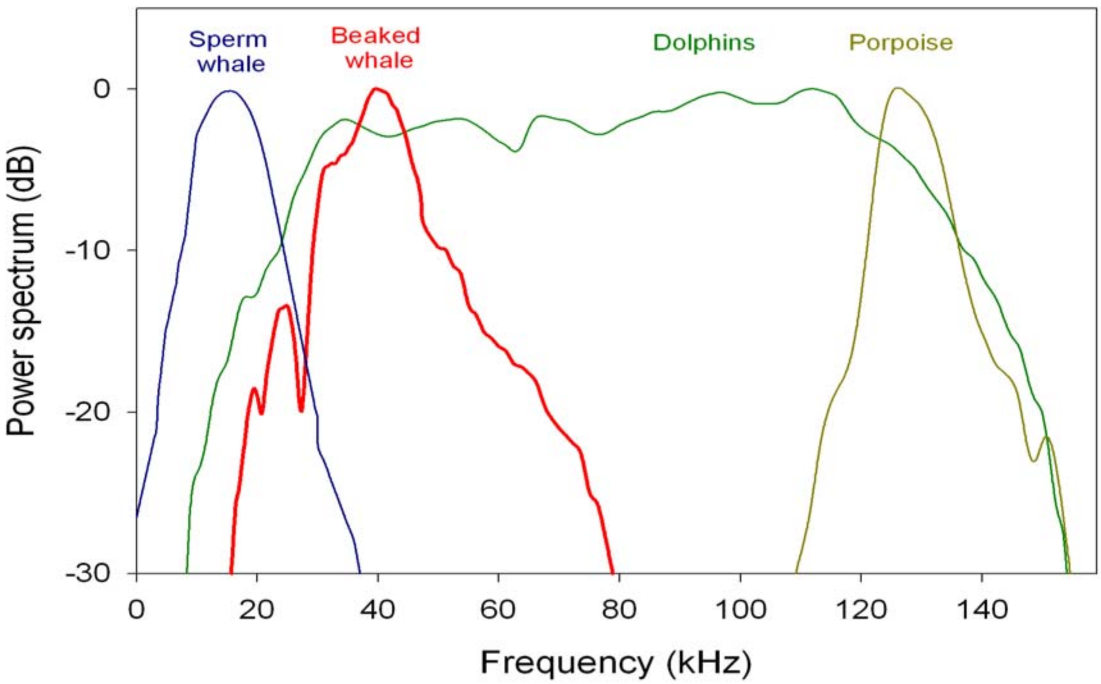


Figure 41. Spectra of click sounds from different odontocete taxa.

As the acoustic characteristics of beaked whale clicks become better defined, there is real potential for acoustic detection and classification of their clicks. This may be of considerable conservation value, since these whales are so difficult to sight. Acoustic monitoring may help define beaked whale habitats and if acoustic monitoring can detect whales at sufficient range, it may help mitigation measures designed to limit exposure to sounds intense enough to harm beaked whales. Figure 41 shows that the spectra of beaked whale clicks are quite distinctive compared to other odontocetes. No other odontocetes are known to produce frequency modulated clicks in this frequency band, offering encouragement that relatively simple detectors may be able to classify and discriminate beaked whale clicks reliably from those of other taxa.

Some of the critical parameters for judging the potential for passive acoustic localization include the source level and beam pattern of the clicks. The best data for estimating source level and beam pattern stems from occasions when the team was able to tag two whales simultaneously. When the tags are synchronized, the distance between the two tagged whales can be estimated by measuring the time it takes for the click to travel from the clicking whale to the tag on the other

whale. The orientation sensors also allow reconstruction of the path of the two whales, constrained by the measured distance between the two. Figure 42 (from Zimmer et al. 2005a) indicates the path of two such simultaneously tagged whales (top) and the distance between them (bottom).

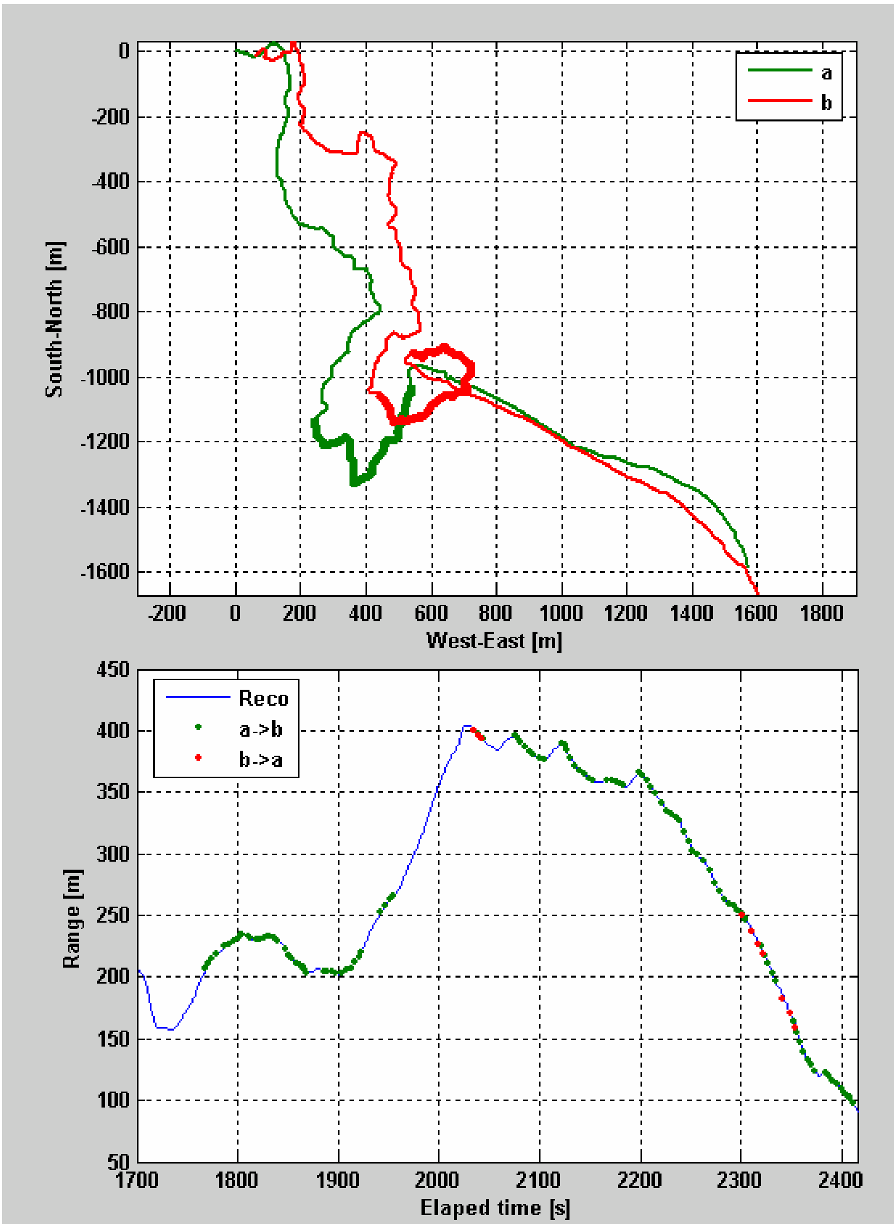


Figure 42. Reconstruction of the tracks of two *Ziphius* carrying tags at the same time. Top panel: Plan view of horizontal components of tracks of whale A (green line) and whale B (red line). The bold portions of the tracks mark the period when whale A approached whale B and the clicks of one tagged whale were also audible on the tag of the other whale. Bottom: Range between the two tagged whales. Each marker represents an acoustic range estimate; '•' describes ranges for clicks emitted by whale A and received by whale B, and '•' corresponds to ranges for clicks from whale B that where received by whale A. (Figure 2 from Zimmer et al. 2005a)

Figure 43 plots the estimated source level of each click from one whale recorded on the other whale, corrected for transmission loss over the known range, as a function of azimuth and elevation.

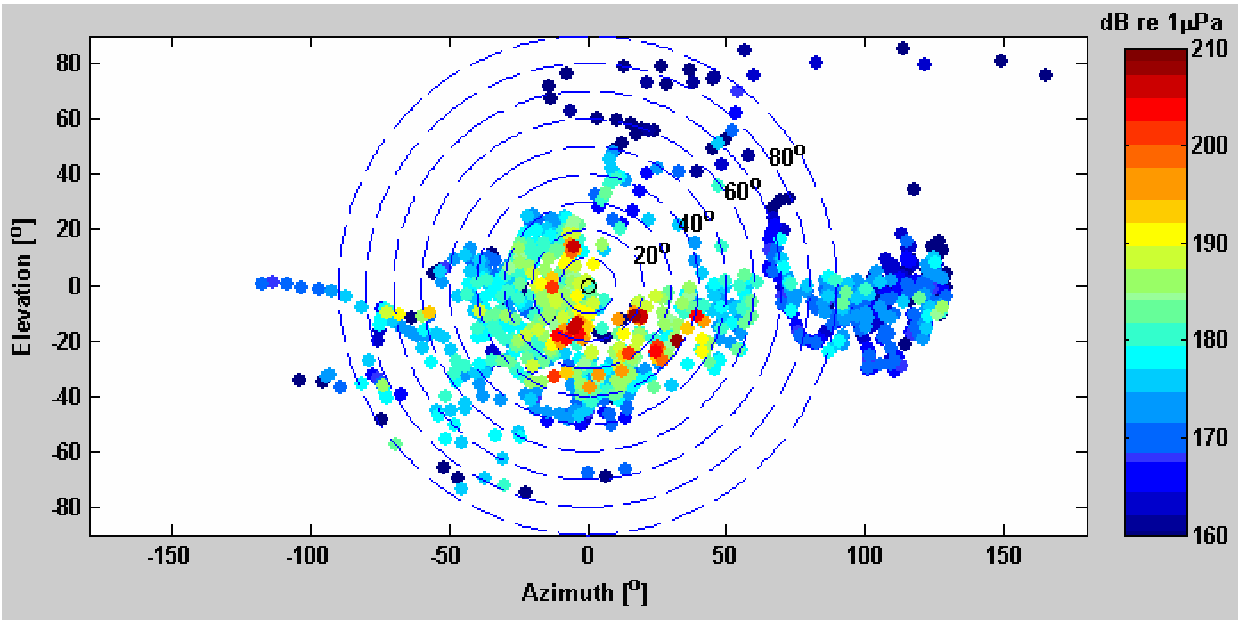


Figure 43. Two dimensional plot of estimated source level of *Ziphius* clicks as a function of azimuth and elevation from the clicking whale's perspective. (Figure 5 from Zimmer et al. 2005a).

Assuming that the beampattern is rotationally symmetric around the axis, the data can be replotted as a function of off-axis angle (Figure 44).

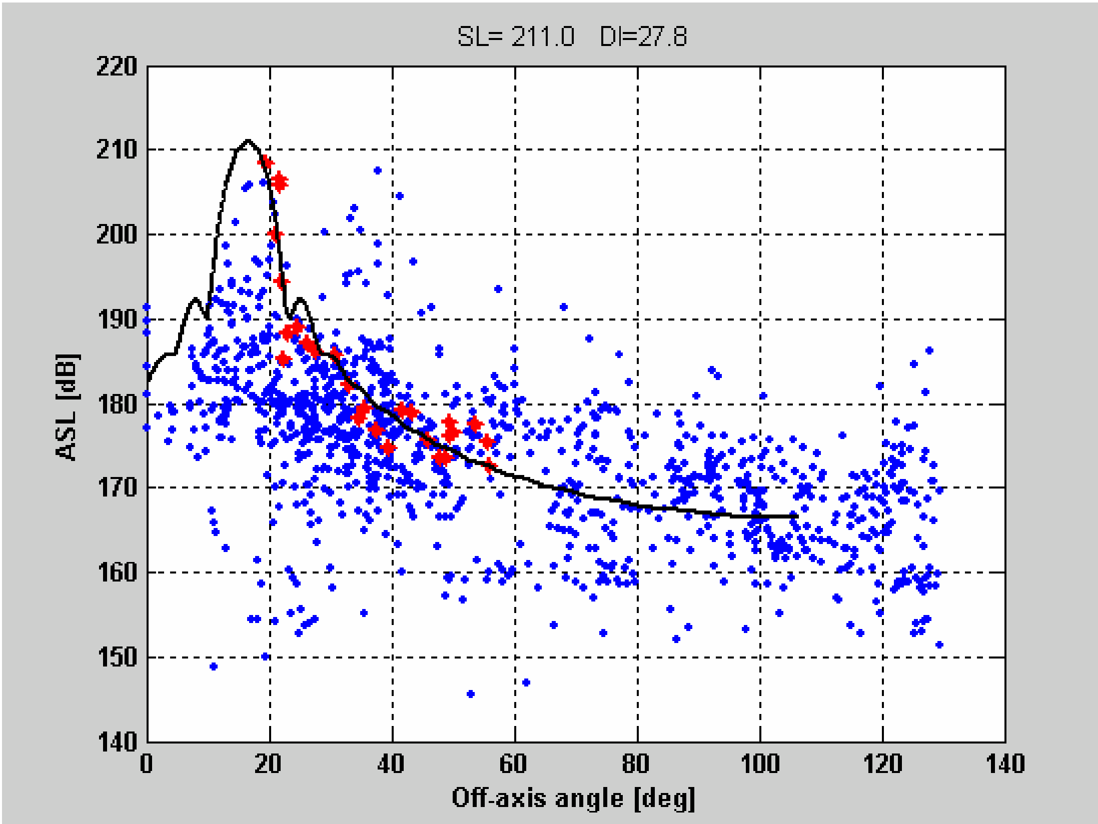


Figure 44. Apparent source level of *Ziphius* clicks as a function of off-axis angle. The 0 angle is defined by the animal's direction of movement. The red points are from a single scan. (Figure 7 from Zimmer et al. 2005a).

These results define the source level and beam pattern of the clicks of *Ziphius*. They suggest a Source Level ~ 214 dB re µPa peak-peak with a -3 dB beamwidth of ±6º, and a Directionality Index of ~ 24 dB. Results for *Mesoplodon* are similar.

5.6 Passive Acoustic Monitoring for Beaked Whales.

Once the spectrum, source level, and beamwidth of beaked whale clicks are known, it is possible to calculate the range at which they can be detected in different noise levels. The detection range for an individual click can be calculated using the sonar equation. The basic concept is that for the signal to be detected, the signal to noise ratio must exceed a detection threshold. The signal to noise ratio can be expressed in decibels as the Source Level (SL) – Directionality Index (DI) – Transmission Loss (TL) – Noise Level (NL). Since location and orientation were known for each beaked whale when they produced each click, the team can model the probability of detecting N successive clicks during a complete foraging dive. Figure 45 plots this probability of detection for 1, 5, and 10 clicks in a row. One of the surprising results of these analyses is that the detection area for a single click during the whole dive is close to the detection area if the clicks were omnidirectional. This means that beaked whales change their orientation so much while clicking and feeding, that they cover nearly all orientations during a deep foraging dive.

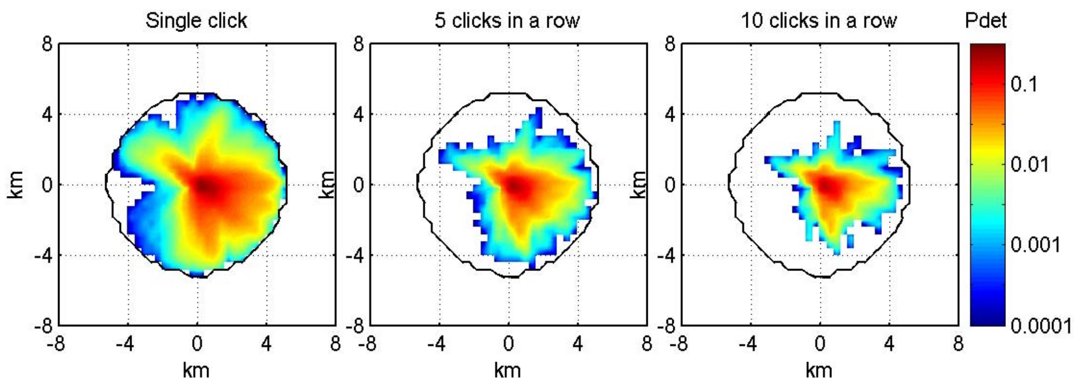


Figure 45. Probability of detecting a single *Ziphius* click during an entire deep foraging dive as a function of source-receiver position for detection threshold (DT) of 16 dB and NL equivalent to sea-state 2. The listening station is assumed located at (0,0) and the black circle indicates the detection area if beaked whales were omni-directional, i.e., excluding the effect of directivity. The colored area indicates where at least one detection was made in an observation interval corresponding to the entire dive. [based on 1 dive of Md04_287a].

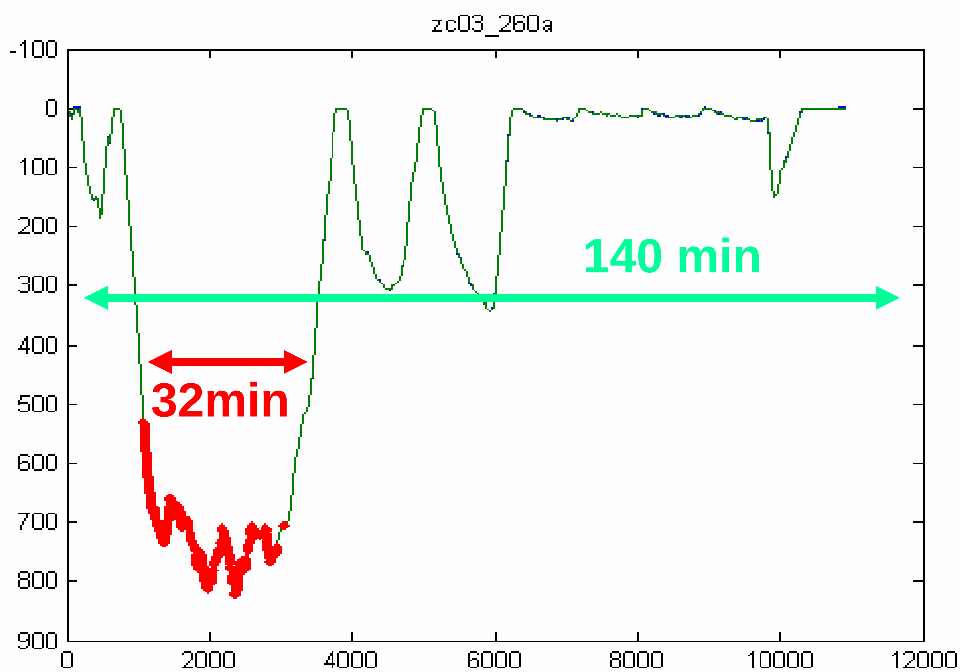


Figure 46. Illustration of 32 min duration of clicking during deep foraging dive, compared to 140 min interval between deep foraging dives. The x-axis is time in seconds and the y-axis is depth in meters.

Figure 45 indicates detection range for one deep foraging dive. Beaked whales tend to make one deep foraging dive roughly every 140 minutes (Figure 46), so it is necessary to monitor for at least this long in order to achieve the probability of detection indicated in Figure 45. If one

listens longer, the range of detection may increase as successive foraging dives cover a broader area (Figure 47).

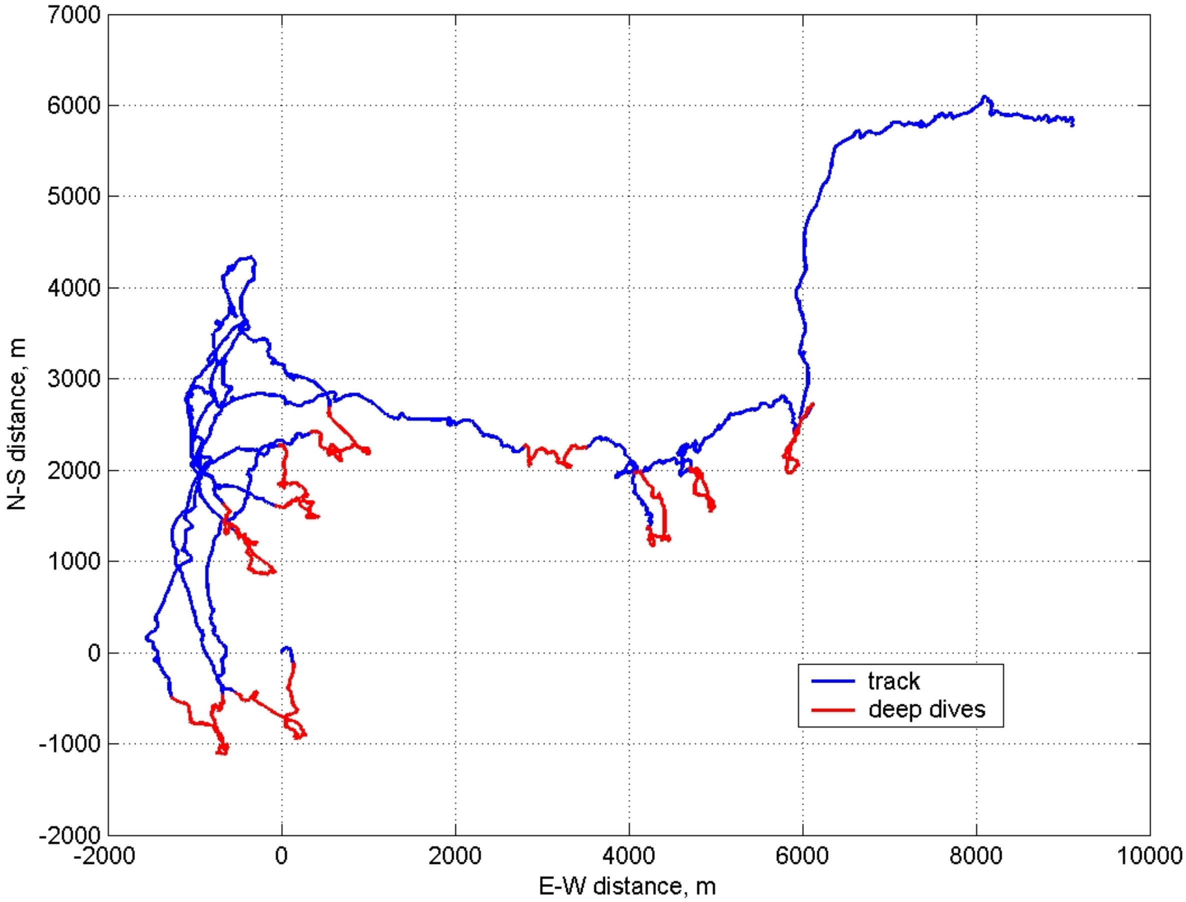


Figure 47. Horizontal view of track of a *Ziphius* tagged in the Ligurian Sea. Silent sections are marked in blue, vocally active sections in red.

Once on-axis click recordings were obtained from the far field, the data were sent to David Moretti's group at NUWC Newport. This group was able to integrate a beaked whale click detector into their real time acoustic monitoring system for the AUTEC range. The typical separation of hydrophones at this range is on the order of 4 km, which is a relatively good match with our model results for probability of detection, so a program was developed to collaborate with the acoustic monitors to validate passive acoustic monitoring for beaked whales. One tool for acoustic monitoring of marine mammals on the range colorizes the location of each hydrophone (which are numbered in sequence on the range) by the number of detections. The color scheme is as follows: blue or black means no detections, green means a low rate, yellow moderate, and red high. Figure 48 illustrates part of the plot of hydrophone locations with beaked whale clicks detected at a high rate on hydrophone 88 and probably the same whale detected at a low rate on hydrophone 89. To verify what is being detected, the monitor can click on the icon

indicating the hydrophone number and view a spectrogram display as shown on Figure 49. The regularity of the clicks and the sharp cutoff in the low frequency of the clicks indicates that this signal is a beaked whale.

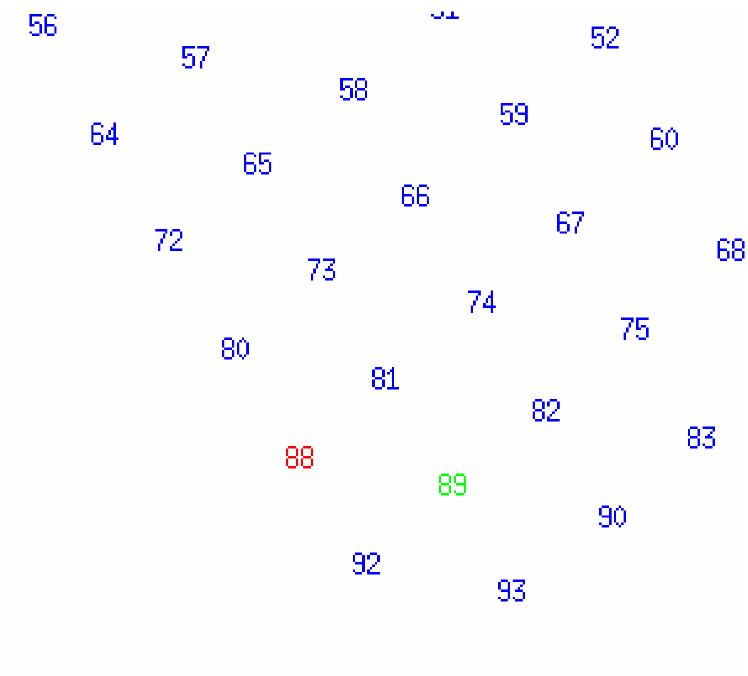


Figure 48. Part of a display from the AUTEC Marine Mammal Monitoring program that colorizes icons indicating the hydrophone location by the number of detections. Courtesy NUWC Marine Mammal Monitoring on Range (M3R).

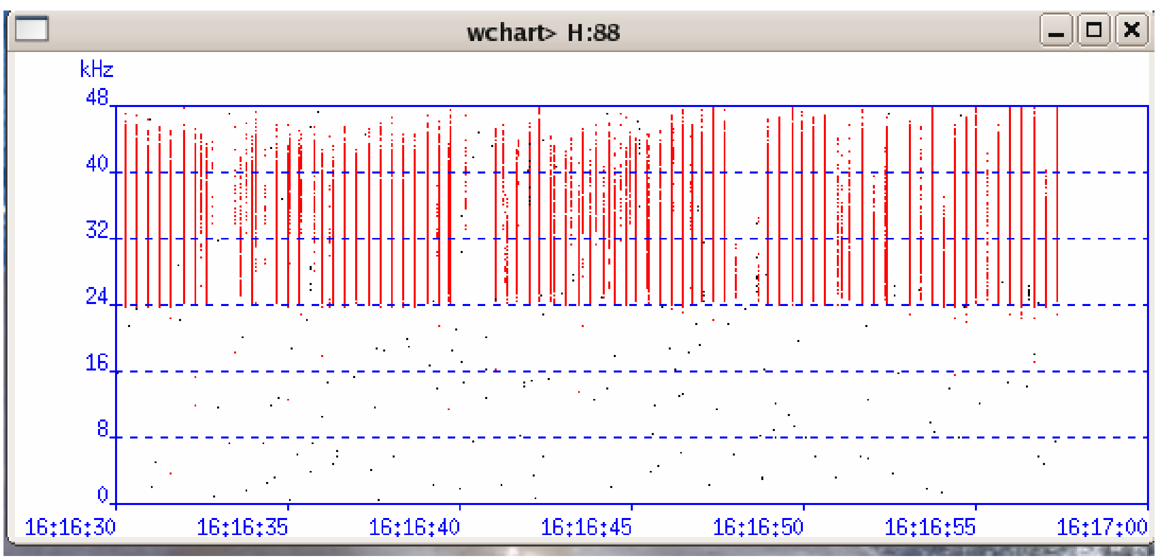


Figure 49. Spectrogram display indicating signal received on hydrophone 88, and showing that the detections are likely beaked whales. Courtesy of NUWC M3R program.

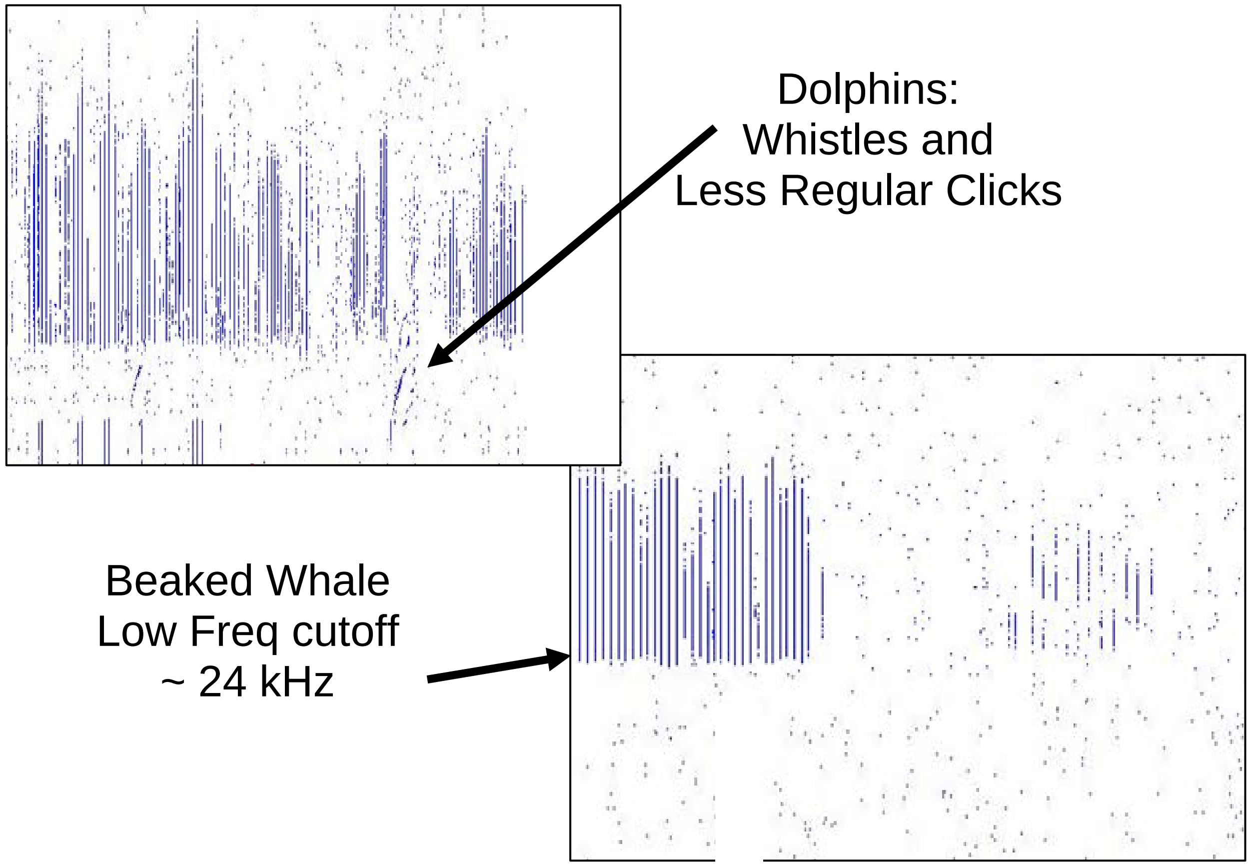


Figure 50. Screen display of NUWC real time marine mammal passive acoustic monitoring system for AUTEC. Figure courtesy of NUWC M3R program

Figure 50 illustrates how acoustic monitors can evaluate data from each hydrophone on the range to check whether the automatic detection and classification system is working correctly. Beaked whale clicks as seen on the lower right have a regular ICI and low frequency cutoff at ~24 kHz. By contrast, dolphins, which are the most common odontocete on the range, produce whistles and less regular clicks as indicated on the upper left.

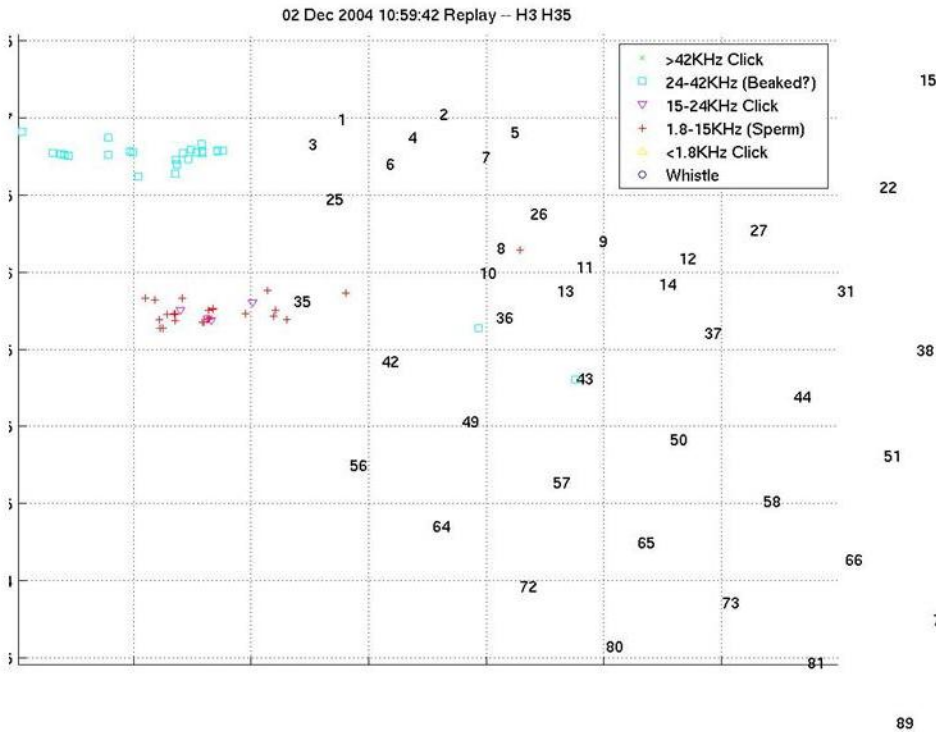


Figure 51. Map of the AUTEC range showing hydrophones indicated by black numbers and clicks identified as beaked whale (aqua squares) and sperm whales (red pluses). Figure courtesy of NUWC M3R program.

The NUWC Marine Mammal Monitoring system can classify clicks in real time. If the same click is recorded on several hydrophones, then the system can localize where the click came from. The map in Figure 51 plots localizations of signals detected and classified into frequency classes linked to marine mammal sounds in real time. This capability allows the acoustic monitors to communicate with small vessels that can be sent out to look for whales.

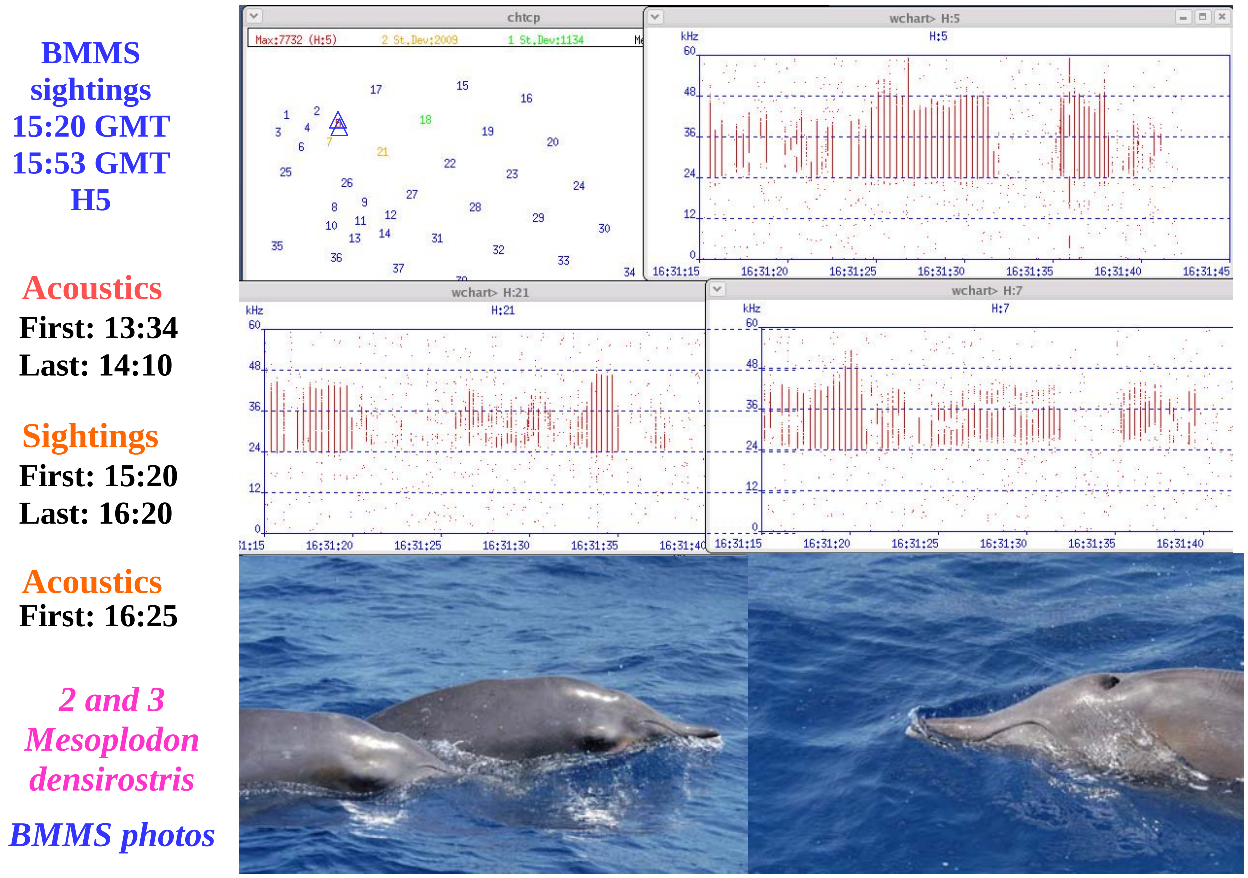


Figure 52. Illustration of a combined acoustic/visual validation cruise. Top left: Map of hydrophones, with detection rate color coded. Blue-black means none, green means a low rate, yellow moderate, and red high. The spectrograms display acoustic data from individual hydrophones and the photos identify whales detected at the location of the blue triangles on the upper left. Figure courtesy of NUWC M3R program. Photos taken by Bahamas Marine Mammal Survey under Bahamian permit issued to Diane Claridge.

Several cruises have been conducted in collaboration with NUWC and the BMMS to validate passive acoustic monitoring. Figure 52 illustrates one of the thirteen times visual monitors were sent to the location of an acoustic detection. The acoustic monitors noted that hydrophone 5 was receiving a lot of hits and hydrophones 7 and 21 nearby were receiving moderate hits. By clicking on the icon for each hydrophone, they were able to call up a spectrogram display and confirm that the signals appeared to be beaked whale clicks. They then directed a sighting vessel operated by the Bahamas Marine Mammal Survey to go to this area, and they sighted *Mesoplodon densirostris* on two occasions at the surface over hydrophone 5. By communicating in real time using radio, the visual and acoustic monitors were able to conduct a combined acoustic and visual follow. For example, the visual monitors stopped sighting their animals at 1620, and the acoustic team started picking up clicks in the area at 1625, suggesting that the animals that had been under observation had started clicking on a deep foraging dive.

No single observation could more clearly illustrate the progress made during this SERDP project for developing new ways to study and understand beaked whales. In the 13 times the acoustic

monitors sent visual monitors to validate an acoustic detection of beaked whales, the visual observers sighted *Mesoplodon densirostris* on 12 times, and an unidentified beaked whale species in the other. Now, the team is clearly ready for an expanded effort at the AUTEC range.

5.7 Effects of Exposure to Anthropogenic Sounds

5.7.1 Opportunistic Study

Aguilar de Soto et al. (2006) report an unusual dive from a *Ziphius* tagged in the Ligurian Sea. During the fourth of a series of eight regular foraging dives, the tag recorded elevated levels of noise from a ship passing nearby. As this noise reached a maximum broadband level of 136 dB rms re 1 μPa, the whale broke off early from its foraging dive and swam to the surface (Figure 53). The ascent rate during this interrupted dive did not differ statistically from the other 7 deep foraging dives of this tagged whale. By the time the whale reached the surface, noise levels had returned to normal, and the whale started a new foraging dive after a short surfacing interval. In this one known case, a beaked whale did respond to noise by surfacing, but not at an unusually high ascent rate.

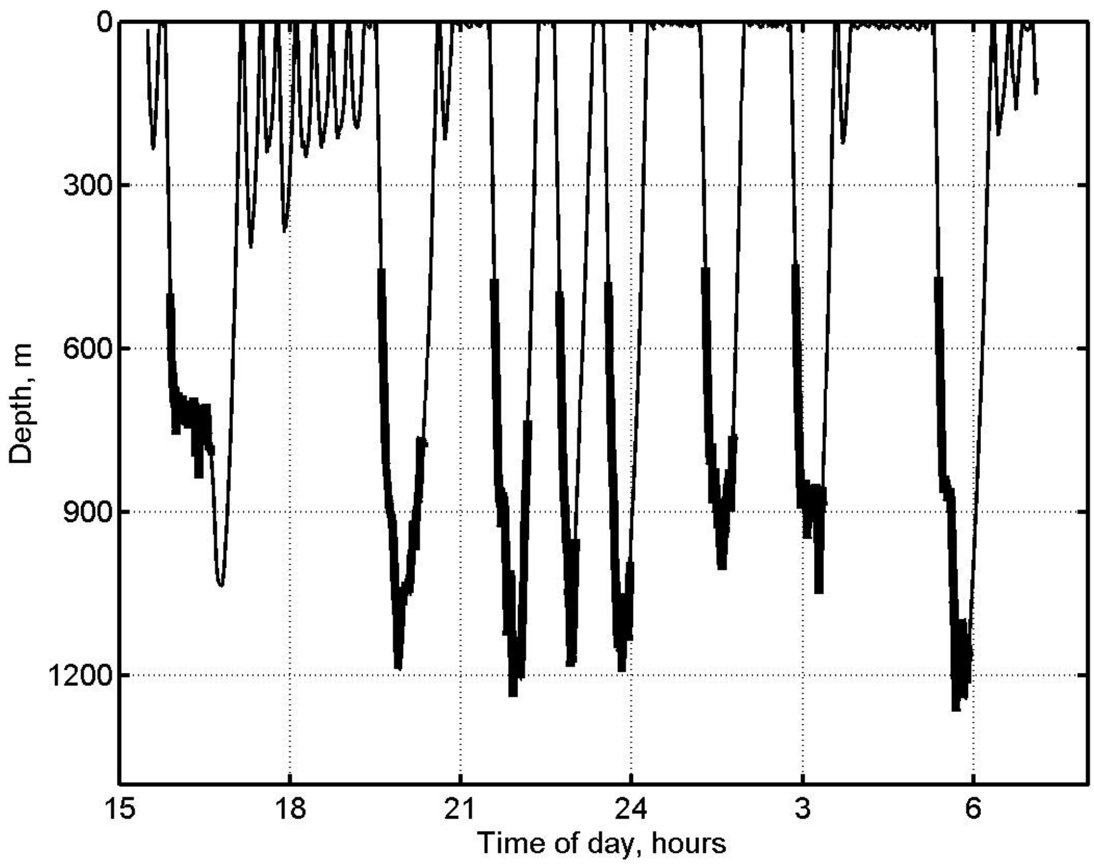


Figure 53. Dive profile of a *Ziphius* tagged in the Ligurian Sea. Bold lines indicate the vocal part of each dive. (Figure 1 from Aguilar et al. 2006)

5.7.2 Controlled Exposures

The data sets obtained from *Ziphius cavirostris* and *Mesoplodon densirostris* to date provide a new insight into the behavior and capabilities of these species. An increased set of baseline data such as those shown here is necessary both to determine normal diving behavior for beaked whales and to identify aspects of their behavior that may increase the risk of exposure to dangerous sound levels. Opportunistic observation of response of a Ziphius to vessel noise has shown that the DTAG is able to detect even subtle responses to sound. Acoustic monitoring on the AUTEC range during times when naval sonar exercises are present or absent may be able to define received levels of sound at which beaked whales may cease clicking prematurely during deep foraging dives.

However, none of the methods listed above has been able to test the many hypotheses about the causal chain of events from sonar exposure to stranding. During many months of field work tagging beaked whales, only one opportunistic response has been detected. One of the critical requirements to detect such a response is a good sample of pre- and/or post-exposure data. One has to be lucky to obtain these control data in opportunistic settings. The most practical way to obtain controlled data on exposure and response is to develop experiments where the scientist can control a sound source to detect responses after baseline data has been collected. The field work capabilities developed in this proposal mean enable the development of this kind of controlled exposure experiment.

The classic purpose of controlled exposure experiments is to develop a dose:response curve in this case for risk to beaked whales as a function of exposure. The known hazard to beaked whales is stranding. Since controlled exposure experiments should be designed to prevent harm to the subjects, a safe indicator response must be developed before one can define the dose:response function. This is similar to studies of hearing, where harmless temporary threshold shifts are used as a proxy for an injurious permanent threshold shift. Therefore, the first goal for controlled exposure experiments should be to establish safe indicators of responses that at louder or longer exposures might pose more risk. With any luck these initial responses may also help narrow the range of hypotheses on the link between sonar exposure and strandings. Once such an indicator response is defined, then it will be possible to titrate acoustic exposure and the indicator response for different stimuli and different species of whale. This dose:response information is critical to managing risk of sonar to toothed whales.

As per a request from the SERDP Executive Director, two appendices are included in this report. Appendix D provides guidance on methods that can determine the near and long-term effects of Naval active acoustics on marine mammals. Appendix E explains how to determine relevant response parameters and safe doses for controlled exposure experiments. Appendix F explains how to determine relevant response parameters for beaked whales in terms of hypotheses linking sonar exposure to strandings, and it discusses a staged protocol for safe exposures.

6. Conclusions

The initial goals of using recording tags to define the behavior and vocalizations of beaked whales were achieved in this project. The DTAG was modified to optimize it for attachment to beaked whales, and its audio sampling was increased to match the high frequencies produced by these whales. When initial field work at AUTEC proved difficult, new sites were found where it was possible to tag the two species, *Ziphius cavirostris* and *Mesoplodon densirostris*, for which atypical mass strandings were most often associated with sonar exercises. These species were discovered to have unusually long and deep dives during which they echolocate to find and capture deep prey. These dives appear to push the physiological limits of these whales, but normal diving behavior appears to involve the aerobic dive limit more than issues of decompression. Beaked whales make about 10 foraging dives a day, vocalizing about 30 min per dive. When in search mode, they produce thousands of distinctive frequency modulated clicks every 0.4 sec and centered around 40 kHz, which are unlike any described previously for toothed whales. The tags not only record outgoing clicks from the tagged whale, but also echoes from prey. When a whale selects a prey item and closes to catch it, at about a body length from the prey, it produces shorter clicks with much faster repetition rates in order to capture the prey.

The echolocation clicks of beaked whales create an opportunity for passive acoustic monitoring of these otherwise elusive animals. Data from far-field on-axis clicks were sent to signal processing engineers at NUWC Newport so that they could develop a beaked whale click detector for their system for passive acoustic monitoring of marine mammals at the AUTEC range in Andros Island, Bahamas. The probability of detecting beaked whales by listening for their sounds has been modeled and results indicate a high probability of detecting beaked whale clicks within a range of about 4 km over a 2-4 hour listening period corresponding to the interval between deep foraging dives. These results were confirmed when the beaked whale detector was run at AUTEC, showing that beaked whales are almost always detectable on the range with typical spacing between hydrophones of about 4 km. This creates a capability for long term monitoring of the location and vocal behavior of marine mammals on the range, one of the goals of this project for effects studies. The surveys in Onslow Bay also provide a baseline for long-term studies on distribution of delphinids as the ESWTR starts operation.

Research sponsored by this project revealed responses of a tagged *Ziphius* to noise from a ship passing nearby, but more research is required to understand the causal chain of events between exposure to sonar and stranding, and to define safe exposures. The results of this project suggest a staged research project on short-term effects of sonar and other naval sounds on beaked and other whales. The first stage would use passive acoustic monitoring of beaked whales on the AUTEC range to observe exposures at which whales cease clicking before the normal vocal phase of foraging dives. The second stage would involve brief exposures to mid-frequency sonar sounds and control stimuli broadcast from an underwater sound source. The goal here would be to observe the sound levels at which whales start to respond, and to use detailed response data in an attempt to narrow the range of hypotheses about the cause of strandings. Once this stage has identified a safe response that can be used as an indicator of response, the project will be ready for a third stage comparing responses of beaked and other whales to several different stimuli. The goal will be to titrate the exposure that elicits the indicator response for each species and stimulus. This stage will not only be used to define dose:response functions for existing naval

signals, but may be able to test novel mitigation strategies, such as alternate signals designed to have low probability of response. Tests with other species will function to define whether other toothed whales are at similar risk from these sounds. Once the third stage has defined dose:response functions, these data can be used to provide a better scientific basis for mitigation measures. The passive monitoring capabilities demonstrated at AUTEC can be ported to other navy underwater ranges and can provide the basis for developing off-range monitoring capabilities as well. The goal of these new monitoring and mitigation measures should be to allow the Navy to use sonar without causing injury to marine mammals, and to develop a capability to monitor for subtler long term effects.

7. References Cited In Report

Aguilar Soto, N., M. Johnson, P. T. Madsen, P. L. Tyack, A. Bocconcelli & Borsani, J. F.2006. Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? *Marine Mammal Science* **22**, 690-699.

Andrew, R. K., Howe, B. M., Mercer, J. A. & Dzieciuch, M. A. 2002. Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustics Research Letters Online* **3**, 65-70.

Anonymous. 1963a. Branco di cetacei oceanici venuti a morire in Liguria. In *Secolo XIX*. Genova.

Anonymous. 1963b. Un branco di cetacei e venuto a morire sulle spiagge di Genova e delle Riviere. In *Il Secolo XIX*. Genova.

Au, W. W. L. 1993. *The Sonar of Dolphins.* Springer-Verlag, New York.

Au, W. W. L., Moore, P. W. B. & Pawloski, D. 1986. Echolocation transmitting beam of the Atlantic bottlenose dolphin. J. Acoust. Soc. Am. **83**, 688–691.

Burgess, W. C., P. L. Tyack, B. J. LeBoeuf & Costa, D. P. 1998. A programmable acoustic recording tag and first results from free-ranging northern elephant seals. *Deep-Sea Research* 45, 1327-1351.

Caldwell, D. K. & Caldwell, M. C. 1971. Sounds produced by two rare cetaceans stranded in Florida, Cetology **4**, 1–6.

Cosens, S. E. & Dueck, L. P. 1988. Responses of migrating narwhal and beluga to icebreaker traffic at the Admiralty Inlet ice edge, N.W.T. in 1986. In *Proc. Conf. on Port and Ocean Engin. Under Arctic Conditions*, (W. Sackinger ed.), pp. 39-54, Fairbanks AK.

Costa, D. P., Crocker, D. E., Gedamke, J., Webb, P. M., Houser, D. S., Blackwell, S. B., Waples, D., Hayes, S. A. & Le Boeuf, B. J. 2003. The effect of a low-frequency sound source (acoustic thermometry of the ocean climate) on the diving behavior of juvenile northern elephant seals, Mirounga angustirostris. *J Acoust Soc Am* **113**, 1155-65.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. & Benner, L. 2006. Why Beaked Whales? Report of Workshop to Understand the Impacts of Anthropogenic Sound. *Journal of Cetacean Research and Management* **7**, 177-187.

D'Amico, A. 1998. Summary Record SACLANTCEN Bioacoustic Panel. La Spezia, Italy: Saclant Centre for Undersea Research.

Evans, D. L. & England, G. R. 2001. Joint Interim Report, Bahamas Marine Mammal Stranding, Event of 15-16 March 2000, pp. 59: U.S. Department of Commerce and Secretary of the Navy.

Fernandez, A., Edwards, J. F., Rodriguez, F., Monteros, A. E. d. l., Herraez, P., Castro, P., Jaber, J. R., Martin, V. & Arbelo, M. 2005. ''Gas and fat embolic syndrome'' involving a mass stranding of beaked whales (Family Ziphiidae) exposed to anthropogenic sonar signals. *Veterinary Pathology* **42**, 446–457.

Finley, K. J., G. W. Miller, R. A. Davis & Greene, C. R. 1990. Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian High Arctic. *Can. Bull. Fish. Aquat. Sci.* 224, 97-117.

Finneran, J. J., Schlundt, C. E., Dear, R., Carder, D. A. & Ridgway, S. H. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. *The Journal of the Acoustical Society of America* **111**, 2929-2940.

Frantzis A. 1998. Does acoustic testing strand whales? Nature **392**, 29.

Frantzis, A., Goold, J. C., Sharsoulis, E. K., Taroudakis, M. I. & Kandia, V. 2002. Clicks from Cuvier's beaked whales, *Ziphius cavirostris* L, J. Acoust. Soc. Am. **112**, 34–37.

Griffin, D. R. 1958. Listening in the Dark: The Acoustic Orientation of Bats and Men. New Haven, Yale University Press.

Hooker, S. K. & Baird, R. W. 1999. Deep-diving behaviour of the northern bottlenose whale, *Hyperoodon ampullatus* (Cetacea: *Ziphiidae*). *Proceedings of the Royal Society of London, B* **266**, 671-676.

Jepson, P. D., Arbelo, M., Deaville, R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herráez, P., Pocknell, A. M., Rodríguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunningham, A. A. & Fernández, A. 2003. Whales, sonar and decompression sickness. *Nature* **425**, 575-576.

Jepson, P. D., Deaville, R., Patterson, I. A. P., Pocknell, A. M., Ross, H. M., Baker, J. R., Howie, F. E., Reid, R. J., Colloff, A. & Cunningham, A. A. 2005. Acute and Chronic Gas Bubble Lesions in Cetaceans Stranded in the United Kingdom. *Vet Pathol* **42**, 291-305.

Johnson, M. P. & Tyack, P. L. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *IEEE Journal of Oceanic Engineering* **28**, 3-12.

Johnson, M. P., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N. & Tyack, P. L. 2004. Beaked whales echolocate on prey. *Proceedings of the Royal Society of London, B* **271**, S383-S386.

Kastak, D. & Schusterman, R. J.1998. Low-frequency amphibious hearing in pinnipeds: methods, measurements, noise, and ecology. *Journal of the Acoustical Society of America* **103**:2216-2228.

LGL & Greeneridge. 1986. Reactions of beluga whales and narwhals to ship traffic and ice-breaking along ice edges in the eastern Canadian High Arctic: 1982-1984. In *Environmental Studies*, pp. 301. Ottowa: Indian and Northern Affairs Canada.

Lynn, S. K. & Reiss, D. L. 1992. Pulse sequence and whistle production by two captive beaked whales, *Mesoplodon* species, Marine Mammal Science **8**, 299–305.

Madsen, P. T., Johnson, M., Aguilar de Soto, N., Zimmer, W. M. X. & Tyack, P. L. 2005. Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*). *The Journal of Experimental Biology* **208**, 181-194.

Malakoff, D. 2001. New sensors provide a chance to listen to the leviathan. *Science* **291**, 577.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P. & Bird, J. E. 1983. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Bolt Beranek and Newman Report No. 5366 submitted to Minerals Management Service, U. S. Dept. of the Interior.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P. & Bird, J. E. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Phase II: January 1984 migration. Bolt Beranek and Newman Report No. 5586 submitted to Minerals Management Service, U. S. Dept. of the Interior.

Marten, K. 2000. Ultrasonic analysis of pygmy sperm whale *Kogia breviceps* and Hubb's beaked whale *Mesoplodon carlhubbsi* clicks, Aquat. Mamm. **1**, 45–48.

Martín, V., Servidio, A. & García, S. 2004. Mass strandings of beaked whales in the Canary Islands. In *Proceedings of the workshop on active sonar and cetaceans.* (ed. P. G. H. Evans & L. A. Miller).

Miksis J. L., M. D. Grund, D. P. Nowacek, A. R. Solow, R. C. Connor & Tyack P.L. 2001. Cardiac Responses to Acoustic Playback Experiments in the Captive Bottlenose Dolphin, *Tursiops truncatus*. Journal of Comparative Psychology **115**, 227-232

Miller, C. A., Morss, M., Arthur, R., Lange, W., Prada, K. & Moore., M. J. 1998. Ultrasonic measurement of blubber thickness in right whales. *SC/M9/RW27 conference paper*.

Miller, L. A., Pristed, J., Møhl, B. & Surlykke A. 1995. The click-sounds of narwhals (*Monodon monoceros*) in Inglefield Bay, Northwest Greenland. Mar. Mamm. Sci. 7, 491-502.

Møhl, B., Wahlberg, M., Madsen, P.T., Heerfordt, A. & Lund, A. 2003. The monopulsed nature of sperm whale clicks. J. Acoust. Soc. Am. **114**, 1143-1154.

Nachtigall, P. E., Pawloski, J. L. & Au, W. W. L. 2003. Temporary threshold shifts and recovery following noise exposures in the Atlantic bottlenosed dolphin (*Tursiops truncatus*). *J Acoust Soc Am* **113**, 3425-3429.

NRC. 1994. Marine Mammals and Low-Frequency Sound. National Academy Press, Washington, D.C.

NRC. 2003. Ocean noise and marine mammals. National Academy Press, Washigton, D.C.

Richardson, W. J., Greene, C. R. Jr., Malme, C. I. & Thomson, D. H. 1995. Marine mammals and noise. New York: Academic Press.

Schlundt, C. E., J. J. Finneran, D. A. Carder & Ridgway, S. H. 2000. Temporary shift in masked hearing thresholds (MTTS) of bottlenose dolphins and white whales after exposure to intense tones. J. Acoust. Soc. Amer. **107**, 3496-3508.

Simmonds, M. P. & Lopez-Jurado, L. F. 1991. Whales and the military. *Nature* **351**, 448.

Tyack, P. L. 1985. An optical telemetry device to identify which dolphin produces a sound. *Journal of the Acoustical Society of America* **78**:1892-1895.

Tyack, P. L., Gordon, J. & Thompson, D. 2004. Controlled Exposure Experiments to Determine the Effects of Noise on Marine Mammals. *Marine Technology Society Journal* **37**, 41-53.

Tyack, P. L. & Johnson, M. P. 2003. Can Controlled Exposure Experiments be Used to Help Determine Safe Exposure for Beaked Whales? - Tools and Techniques for Quantifying the Responses of Whales to Sound. In *Proceedings of the Workshop on Active Sonar and Cetaceans; European Cetacean Society's 17th Annual Conference*, pp. 43-47. Las Palmas, Gran Canaria.

Tyack, P. L., Johnson, M., Soto, N. A. d., Sturlese, A. & Madsen, P. T. 2006. Extreme diving behaviour of beaked whale species known to strand in conjunction with use of military sonars. *Journal of Experimental Biology*. **209**, 4238-4253

Tyack, P. L. & Recchia, C. A. 1991. A datalogger to identify vocalizing dolphins. *Journal of the Acoustical Society of America* **90**:1668-1671.

Urick R. J. 1986. *Ambient noise in the sea.* Peninsula Publishing, Los Altos, CA.

Watkins, W. A., K. Moore & Tyack, P. 1985. Sperm whale acoustic behaviors in the southeast Caribbean. *Cetology* **49**, 1-15.

Watkins, W. A. & Schevill, W. E. 1975. Sperm whales (*Physeter catodon*) react to pingers. *Deep Sea Research I* **22**, 123-129.

Watwood, S. L., Miller, P. J. O., Johnson, M., Madsen, P. T. & Tyack, P. L. 2006. Deep-diving foraging behavior of sperm whales (*Physeter macrocephalus*). *J. Animal Ecology*.

Zimmer, W. M. X., Johnson, M. P., Madsen, P. T. & Tyack, P. L. 2005a. Echolocation clicks of Cuvier's beaked whales (*Ziphius cavirostris*). *Journal of the Acoustical Society of America* **117**, 3919-3927.

Zimmer, W. M. X., Tyack, P. L., Johnson, M. P. & Madsen, P. T. 2005b. Three-dimensional beam pattern of regular sperm whale clicks confirms bent-horn hypothesis. *The Journal of the Acoustical Society of America* **117**, 1473-1485.

Appendices

Appendix A. Acoustic and visual detection data of marine mammals on the AUTEC range

Appendix B. List of Technical Publications

Appendix C. Other Technical Material

Appendix D. Guidance on how to determine the near- and long-term effects of naval active acoustics on marine mammals.

Appendix E. How to determine the relevant response parameters and safe doses for Controlled Exposure Experiments.

Appendix A. Table A1. Acoustic and visual detection data of marine mammals on the AUTEC range

Test	Date	Visual Observers	Species (Scientific Name)	Species (Common Name)	Acoustic	Visual	# Animals Sighted	Multispecies Group
1	3/25/2002	WHOI	*Physeter macrocephalus*	Sperm whale	Y	Y	3 (1-3)	no
1	3/28/2002	WHOI	*Mesoplodon densirostris*	Blainville's beaked whale	N	Y	6 (4-7)	no
1	3/28/2002	WHOI	*Mesoplodon densirostris*	Blainville's beaked whale	N *	Y	1	no
1	3/30/2002	WHOI	*Physeter macrocephalus*	Sperm whale	Y	Y	1 (1-2)	no
1	4/1/2002	WHOI	*Globicephala macrorhynchus*	Short-finned pilot whale	Y	Y	23 (2-25)	no
1	4/2/2002	WHOI	unidentified *Odontoceti*	unidentified Odontocete	N**	Y	1	no
1	4/2/2002	WHOI	unidentified *Odontoceti*	unidentified Odontocete	N**	Y	1	no
1	4/2/2002	WHOI	unidentified *Odontoceti*	unidentified Odontocete	N**	Y	1	no
1	4/3/2002	WHOI	*Physeter macrocephalus*	Sperm whale	Y	Y	1	no
1	4/4/2002	WHOI	unspecified *Ziphiidae*	unspecified beaked whale	N	Y	2	no
1	4/4/2002	WHOI	unspecified *Ziphiidae*	unspecified beaked whale	N	Y	1	no
1	4/4/2002	WHOI	*Peponocephala electra*	Melon-headed whale	Y	Y	50	P. electra, S. bredanensis
1	4/4/2002	WHOI	*Steno bredanensis*	Rough-toothed dolphin	Y	Y	25	P. electra, S. bredanensis
1	4/5/2002	WHOI	*Peponocephala electra*	Melon-headed whale	Y	Y	8	P. electra, S. bredanensis
1	4/5/2002	WHOI	*Steno bredanensis*	Rough-toothed dolphin	Y	Y	12	P. electra, S. bredanensis
2	1/8/2003	Univ. of Hawaii	*Kogia breviceps*	Pygmy sperm whale	N	Y	3	no
2	1/8/2003	Univ. of Hawaii	unidentified *Delphinidae*	unidentified dolphin	N	Y	7	no
2	1/8/2003	Univ. of Hawaii	unidentified *Ziphiidae#*	unidentified beaked whale	?***	Y	5	no
2	1/8/2003	Univ. of Hawaii	*Kogia breviceps*	Pygmy sperm whale	?	Y	1	no
2	1/8/2003	Univ. of Hawaii	unidentified *Delphinidae*	unidentified dolphin	?	Y	4	no
2	1/10/2003	Univ. of Hawaii	unidentified *Delphinidae*	unidentified dolphin	?	Y	1	no
2	1/11/2003	Univ. of Hawaii	*Stenella coeruleoalba*	Striped dolphin	Y	Y	14	no
2	1/11/2003	Univ. of Hawaii	*Physeter macrocephalus*	Sperm whale	Y	Y	1	no
2	1/11/2003	Univ. of Hawaii	unidentified *Delphinidae*	unidentified dolphin	Y?	Y	8	no
2	1/11/2003	Univ. of Hawaii	unidentified *Delphinidae*	unidentified dolphin	N**	Y	4	no
2	1/12/2003	Univ. of Hawaii	*Physeter macrocephalus*	Sperm whale	Y	Y	1	no
2	1/12/2003	Univ. of	*Megaptera novaeangliae*	Humpback whale	N	Y	1	no

		Hawaii						
2	1/12/2003	Univ. of Hawaii	*Steno bredanensis*	Rough-toothed dolphin	Y	Y	15	no
3	4/27/2005	BMMS	unknown *Ziphiidae*	unknown beaked whale	Y	Y	1	no
3	4/27/2005	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	2-3	no
3	4/27/2005	BMMS	*Stenella attenuata*	Pantropical spotted dolphin	Y	Y	2-5	no
3	4/28/2005	BMMS	*Globicephala macrorhynchus*	Short-finned pilot whale	N****	Y	45-50	no
4	9/24/2005	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	2	no
4	9/24/2005	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	3	no
4	9/24/2005	BMMS	*Globicephala macrorhynchus*	Short-finned pilot whale	Y	Y	2	no
4	9/26/2005	BMMS	*Globicephala macrorhynchus*	Short-finned pilot whale	Y	Y	21	no
4	9/27/2005	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	2	*M. densirostris, K. breviceps ?*
4	9/27/2005	BMMS	*Kogia breviceps*	Pygmy sperm whale	N?	Y	2	*M. densirostris, K. breviceps ?*
4	9/27/2005	BMMS	*Kogia breviceps*	Pygmy sperm whale	N?	Y	1	*M. densirostris, K. breviceps ?*
4	9/27/2005	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	5	no
4	9/27/2005	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	4	no
4	9/29/2005	BMMS	*Steno bredanensis*	Rough-toothed dolphin	Y	Y	20	no
4	9/30/2005	BMMS	*Globicephala macrorhynchus*	Short-finned pilot whale	Y	Y	60	*G. macrorhynchus, S. bredanensis*
4	9/30/2005	BMMS	*Steno bredanensis*	Rough-toothed dolphin	Y?**	Y	15	*G. macrorhynchus, S. bredanensis*
4	9/30/2005	BMMS	*Steno bredanensis*	Rough-toothed dolphin	?**	Y	13	no?
5	3/6/2006	WHOI	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	3	no
5	3/6/2006	BMMS	*Mesoplodon densirostris*	Blainville's beaked whale	Y	Y	1	no

Appendix B. List of Technical Publications

1. Articles or papers published in peer-reviewed journals

Aguilar de Soto, N., Johnson, M., Madsen, P. T., Tyack, P. L., Bocconcelli, A. & Borsani, J. F. 2006. Does intense ship noise disrupt foraging in deep-diving Cuvier´s beaked whales (*Ziphius cavirostris*). *Marine Mammal Science*. 22:690-699.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. & Benner, L. 2006. Why Beaked Whales? Report of Workshop to Understand the Impacts of Anthropogenic Sound. *Journal of Cetacean Research and Management*, 7(3):177-187.

Johnson, M., P. T. Madsen, W. M. X. Zimmer, N. Aguilar de Soto, and P. L. Tyack. 2006. Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation. *Journal of Experimental Biology* **209**:5038-5050.

Johnson M., Madsen P. T., Zimmer W. M. X., de Soto N. A., Tyack P. L. 2004. Beaked whales echolocate on prey. Proceedings of the Royal Society B [Biology Letters] 271:S383-S386. **DOI:** 10.1098/rsbl.2004.0208

Johnson M. and P. L. Tyack. 2003. A Digital Acoustic Recording Tag for Measuring the Response of Wild Marine Mammals to Sound. IEEE Journal of Oceanic Engineering 28:3-12.

Madsen P.T., Johnson M., Aguilar DeSoto N., Zimmer W.M.X. and Tyack P. 2005. Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*). Journal of Experimental Biology 280:181-194

Tyack, P; Gordon, J. and D. Thompson. 2004. Controlled exposure experiments to determine the effects of noise on large marine mammals. Marine Technology Society Journal, 37(4): 41-53.

Tyack, P. L., Johnson, M., Aguilar de Soto, N., Sturlese, A. & Madsen, P. T. 2006. Extreme diving behaviour of beaked whale species known to strand in conjunction with use of military sonars. *Journal of Experimental Biology* **209**:4238-4253.

Wartzok D, J. Altmann, W. Au, K. Ralls, A. Starfield, P. L. Tyack. 2005. Marine Mammal Populations and Ocean Noise: Determining when noise causes biologically significant effects. (NRC report) Washington, D.C.: National Academy Press.

Watwood, S. L., Miller, P. J. O., Johnson, M., Madsen, P. T. and Tyack, P. L. 2006. Deep-diving foraging behavior of sperm whales (*Physeter macrocephalus*). *J. Animal Ecology* **75**:814-825.

Zimmer W. M.X., M. P. Johnson, A. D'Amico, P. L. Tyack. 2003. Combining data from a multi-sensor tag and passive Sonar to determine the diving behavior of a sperm whale (*Physeter macrocephalus*). IEEE Journal of Oceanic Engineering 28:13-28.

Zimmer W. M. X., Johnson M., Madsen P. T., Tyack P. L. 2005. Echolocation clicks of Cuvier's beaked whales (*Ziphius cavirostris*). Journal of the Acoustical Society of America 117:3919-3927

2. Technical reports

Research Program to evaluate effects of manmade noise on marine mammals in the Ligurian Sea. Report to Scientific Committee of ACCOBAMS for discussion at Istanbul, Turkey. 19 November 2003.

3. Conference/Symposium Proceedings and/or Papers

J. Gordon, D. Thompson & P. Tyack. The Use of Controlled Exposure Experiments to Investigate the Effects of Noise on Marine Mammals: Scientific, Methodological, and Practical Considerations. Report of a workshop at the European Cetacean Society, Rome Italy. 10 May 2001

Studying disruption of marine mammal behavior due to manmade noise, National Academy of Sciences, Committee on Ambient Noise and Marine Mammals, Woods Hole, June 2001

Effects of noise on marine mammals, invited plenary speech, 14th Biennial Conference on the Biology of Marine Mammals, Society for Marine Mammalogy, 29 Nov 2001, Vancouver

Marine mammals and sonar: research for acoustic risk mitigation, Underwater Defense Technology Europe 2002, 19 June 2002, La Spezia Italy

"Partners in Environmental Technology" Technical Symposium & Workshop, Alexandria Virginia, December 3-5 2002.

Workshop on Active Sonar and Cetaceans, European Cetacean Society, Las Palmas, Canary Islands Spain, 8 March 2003

Controlled exposure experiments to determine safe exposure for beaked whales. *Proceedings of the workshop on active sonar and cetaceans.* (ed. P. G. H. Evans & L. A. Miller). European Cetacean Society, 8 March 2003, Las Palmas, Gran Canaria Spain

Acoustic and diving behavior of sperm whales (*Physeter macrocephalus*) as recorded from a digital acoustic recording tag. European Cetacean Society, 10 March 2003, Las Palmas, Gran Canaria Spain

Environmental Consequences of Underwater Sound Workshop/Symposium, San Antonio Texas, May 12-16, 2003.

Responses of DTAGed Sperm Whales to CEE. Environmental Consequences of Underwater Sound (ECOUS) Symposium, San Antonio 12 May 2003

Behavioral Impacts of Noise on Marine Mammals. First Plenary Meeting of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, Bethesda MD, 3-5 Feb 2004. http://www.mmc.gov/sound/plenary1/pdf/plenary%201_tyack.pdf

Presentations on diving and vocal behaviors of tagged beaked whales. Beaked Whale Technical Workshop of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, Baltimore MD, 13-16 April 2004

Second Plenary Meeting of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, Arlington VA, 28-30 April 2004

Third Plenary Meeting of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, San Francisco CA, 27-29 July 2004

International Workshop of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, London, 28-30 Sept 2004

Fourth Plenary Meeting of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, New Orleans, LA, November 30, December 1-2, 2004

Tagging research on beaked whales. Environmental Consequences of Underwater Sound Sypmposium, 17 March 2005

Report of the Ad-Hoc Group on the Impact of Sonar on Cetaceans. International Council on the Exploration of the Sea, 2005

Research priorities to reduce risk to beaked whales from military sonar, European Cetacean Society, Workshop, La Rochelle France, 3 April 2005

Fifth Plenary Meeting of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, Silver Spring Maryland, April 19-21, 2005

Effects of sound in the ocean on marine life, Lerici, Italy, May 2005

Marine Mammal Monitoring for Navy Ranges, Crystal City, VA, 7-8 Sept 2005

Sixty Plenary Meeting of Marine Mammal Commission Federal Advisory Committee on Acoustic Impacts on Marine Mammals, Bethesda, MD, September 20-22, 2005

The effects of anthropogenic sound on marine mammals: A draft research strategy. Report of a workshop held at Oxford, 4-9 October 2006

4. **Published Technical Abstracts**
5. **Published Text Books or Book Chapters**

2005 Wartzok D, J. Altmann, W. Au, K. Ralls, A. Starfield, P. L. Tyack. Marine Mammal Populations and Ocean Noise: Determining when noise causes biologically significant effects. (NRC report) Washington, D.C.: National Academy Press.

Appendix C. Other Technical Material

6. **Patents**
7. **Protocols**
8. **EPA/State Regulatory Permits**
   NMFS Permit no. 981-1578-02
   NMFS Permit no. 981-1707-00
9. **Awards**

Project of the Year for Sustainable Infrastructure, SERDP, Dec 2005

10. Scientific/technical honors received

Walter A. and Hope Noyes Smith Chair, WHOI 2001

Appendix D. Guidance on how to determine the near- and long-term effects of naval active acoustics on marine mammals.

Peter Tyack
Biology Department
WHOI

This appendix reviews a series of steps needed for a research program to evaluate risk factors to beaked whales from behavioral responses to anthropogenic sounds. There are two main ways to study behavioral effects of sound on wild animals: experiments in which the scientist controls the sound source, and observational studies in which the scientist studies responses of subjects to sounds being made for other reasons (Tyack et al. 2004). Each approach has strengths and weaknesses for studying the responses of whales to naval sonars. Controlled experiments are the best way to prove cause and effect between sound and a response, and are well suited for studying short-term effects of sources that are relatively easy and cheap to deploy. Some species of marine mammal can be kept under continuous observation, but for many species technological methods are required to measure exposure at the animal and to measure responses. WHOI engineer Mark Johnson has developed a tag that can measure sound at the animal and can measure sound, depth, and orientation, which provides sufficient response measures to test many hypotheses. Scientists would typically use an experimental sound source that is less directional and less powerful than an actual sonar. This makes it easier and more practical to control sound exposure during tagging operations and to plan the sound exposure at a specific level and duration. Such an experiment would typically start with low-level short-duration exposures, and slowly increase level or duration until a response is first observed. This reduces the risk to the subject, but at the expense that the exposure differs from actual sonar exercises. On the other hand, with the alternate approach of observing a naval sonar exercise, scientists would have little control over the exposure of animals tagged before or during an exercise, so it is likely to take longer and more exposures to obtain a sufficient sample size. Less detailed response measures than tagging may therefore be better suited to this kind of observational study. If tagging is to be used, it may demand attachment durations several times longer than the exercise duration if pre-exposure and post-exposure data are to be part of the design. If a first experimental phase demonstrates that relatively easy-to-monitor responses can be linked to risk, then these results can be used to develop methods to monitor long-term for responses to actual naval operations.

This document suggests a phased series of observational and experimental studies that mirror the standard process of risk assessment (Harwood 2000). The first step in this process is hazard identification. Strandings of beaked whales coincident with naval sonar exercises stand out as the one case of known lethal impact of human use of sound underwater (Wartzok et al. 2005). Since this is the most extreme effect known, it will be used as an example for the rest of this document. Other species and other stimuli may be used to compare for differential responses and risk. The second steps in risk assessment involve assessing dose:response relations and the distribution of exposures to the animals. Once the consequences and extent of exposure have been delineated, then and only then does it become possible to characterize the risk to the population. Once the risks have been characterized, then one can come up with strategies to manage the risk. Before this point, the most obvious management actions are to limit exposure, without knowing how much this reduction actually reduces risk.

The primary uncertainties that impede our ability to manage risks of sonar to beaked whales involve our ignorance of the causal chain of events between exposure to sonar and stranding, and the lack of effectiveness of current methods to monitor for beaked whales. Enough is known about sonar signals and how they propagate to predict levels received by the whale as long as one knows where the whales are and one knows the relevant environmental parameters. Work sponsored by SERDP SI-1188 in collaboration with the NUWC marine mammal monitoring project at the AUTEC naval range has provided a breakthrough in the ability to monitor beaked whales on a navy range. While beaked whales are notoriously difficult to sight, tagging of beaked whales has defined their vocal behavior sufficiently to estimate the probability of detecting beaked whales by passive acoustic monitoring. Beaked whales make about 15000 clicks per foraging dive (Johnson et al. 2004; Madsen et al. 2005), and all whales tagged made a foraging dive every 120-140 min on average. Modeling suggests a high probability of detection of a foraging dive for hydrophones near the depth at which beaked whales feed (~500-1500m) separated by up to 4 km (Tyack et al. 2006a). The Atlantic Underwater Test and Evaluation Center (AUTEC) at Tongue of the Ocean has such an array, and David Moretti's group at NUWC used tag data to develop a simple detector for beaked whales which detected clicks from the AUTEC array that appeared to be beaked whales. With support from SERDP, WHOI has collaborated with NUWC and Diane Claridge of the Bahamas Marine Mammal Survey to ground truth the beaked whale detections. The results of the field efforts strongly support the conclusion that beaked whales are very likely to be detectable with passive acoustic monitoring during intervals of two to four hours, long enough for a foraging dive to be likely.

The critical next step in terms of dose:response studies is to design short-term experiments that can safely study initial responses of beaked whales to short exposures to sonar-like sounds in order to help understand the cause of strandings, and to develop a safe indicator response that can be used to find out what exposures cause the response. Controlled exposure experiments to study responses of marine mammals to anthropogenic sounds have been conducted for decades (e.g. Malme et al. 1985). For a CEE to have a truly controlled exposure, it is essential to have real time monitoring in place for the subject. It is also important to monitor for any other marine mammals that may be nearby to avoid unanticipated exposures of animals that are not subjects of the experiment. Propagation from the source to the animal must be understood well enough to control the exposure at the animal – this often requires environmental information as well as propagation modeling. Beaked whales are so difficult to sight that it is essential to use passive acoustic monitoring for this capability. AUTEC is the only site where this need can currently be met. One site may be sufficient for initial pilot studies of how beaked whales respond to exposures, but any complete set of experiments would require working at other sites where the animals are more naïve with respect to sonar signals, and with other populations, ideally including *Ziphius*, which is seldom sighted at AUTEC, but which dominates the strandings that coincide with sonar exercises. A critical enabler for work in other sites will involve ship-deployed portable monitoring systems. WHOI and NURC are working on sensors that can be deployed from a ship or autonomous underwater vehicle (AUV) or installed in buoys that can deploy hydrophones several 100 m deep and radio data back to the ship.

Effective real-time monitoring creates an opportunity for studying responses of beaked whales at AUTEC to sonar signals. Since beaked whales dive so long and only click for part of the time, it

is necessary to use a tag to record exposure at the animals and for continuous measurement of responses. The DTAG was designed not only to record sounds produced by whales, but also to provide sensitive and continuous sampling of acoustic exposure from anthropogenic sounds, along with any behavioral responses. Its utility has been demonstrated in observational studies with beaked whales (Aguilar de Soto et al. 2006) and in carefully designed and controlled exposure experiments with sperm whales (Madsen et al. 2006). The more sensitive the methods used to detect responses of the subjects, the more complete the response measures. However, no experiment can prove that subjects did not respond at all. Rather, experiments should be designed to test hypotheses about the dosage required to elicit specific responses (Tyack et al. 2004), and the response measures should be selected to test the specific hypotheses. Appendix E describes all of the hypotheses proposed to date relating sonar exposure to stranding and describes how the tag can be outfitted with sensors to measure all of the response measures relevant for detecting behavioral effects.

As described in the first paragraph of this appendix, two different approaches to these preliminary studies are possible: observation of beaked whales near actual sonar exercises or short low-level playbacks with an underwater speaker. Observational studies would probably require tagging whales before an exercise started, both to collect pre-exposure control data, and because it is unlikely civilians could tag near ongoing exercises. This would require a significant increase in the duration of tag attachment from roughly one day to near a week. If biologists cannot follow the tagged whale during the exercise, it would also require some new way to recover the tag. The current tag contains a VHF transmitter which would enable later recovery, but might require aerial survey along with a vessel to recover the tag. Distant tags have been recovered in this way, but some modifications to the tag may decrease the cost of the recovery effort and increase its reliability. The simplest innovation may be to incorporate a GPS sensor on the tag, along with the ability to telemeter location.

The second approach would involve intentional exposure of a tagged beaked whale to a short sonar-like sound. If the goal of this work was simply to detect an initial response indicating risk of stranding, it might not have to involve all the features of a real sonar exercise. For example, broadcasting a few minutes of sonar sounds through a small underwater speaker when a whale was foraging at depth or breathing at the surface might identify which of the hypotheses listed above was the most likely risk factor. Such an experiment would not require additions to the techniques demonstrated in current field work. There is debate about the observational studies vs the cost of adding extra signals in an experiment, but starting with the low level experiment seems the most conservative approach given all of the uncertainties re tagging studies associated with an exercise at this point.

An important element of the design of controlled exposure experiments involves deciding the range of exposures to test. In the case of beaked whales, one would want to start exposures at the level where responses may begin and to be limited to responses that would not pose a risk to the subject. Appendix E describes a method to define a safe exposure range. Determination of the minimum and maximum exposures for the first experiments at AUTEC could be based upon observations of cessation of vocalization during actual sonar exercises. One of the first expected disturbance reactions of a whale foraging at depth would be cessation of echolocation used to find food, and range monitoring has detected apparent silencing reactions during some sonar

exercises. If the range hydrophones are calibrated, one can measure the received level of sonar signals at the hydrophones near clicking whales. If the location of the sonar and environmental data required to model sound propagation are known, then one can estimate the received level of the sonar at whales when they do or do not stop clicking. Tag data have never recorded a vocal interval of less than 17 minutes from undisturbed beaked whales, and control data from listening at AUTEC can define the distribution of vocal intervals under undisturbed conditions. Statistical analysis of the distribution of vocal intervals during sonar exposure should be able to define probability of a response. Those shown to stop could be tallied separate from those that do not to yield something like the following plot:

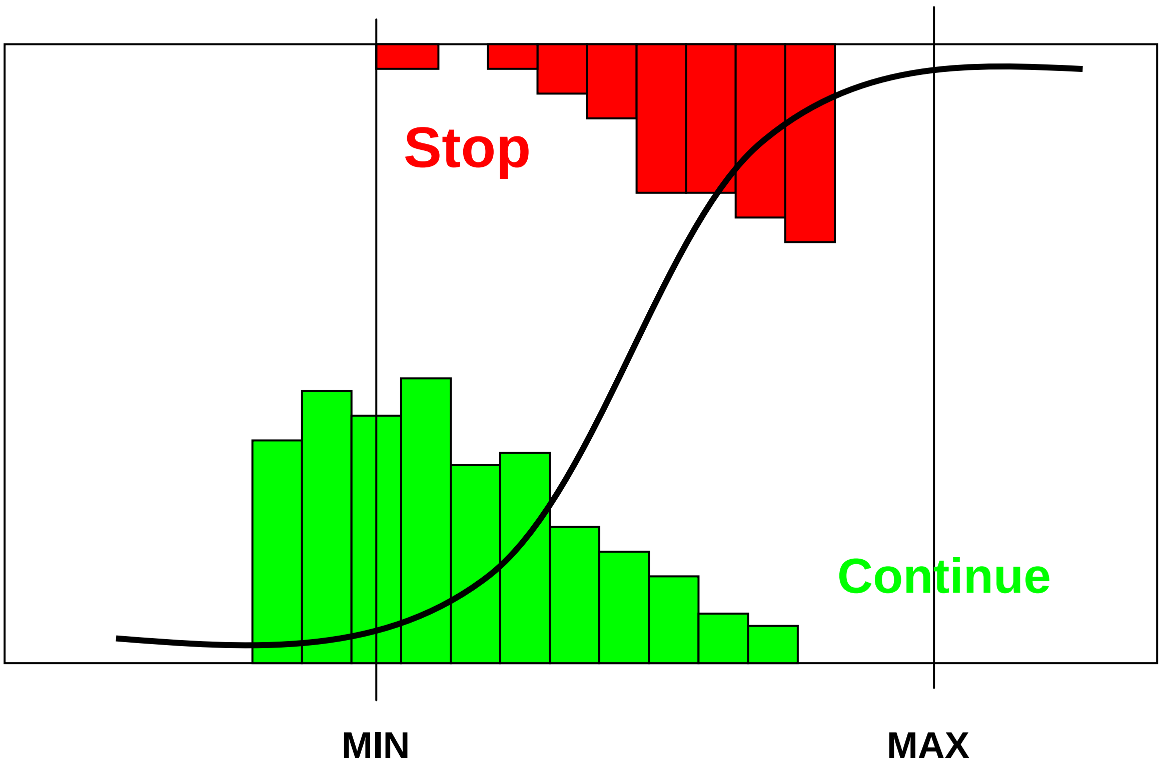


Figure D1. Illustration of method to determine minimum and maximum exposure levels for exposure experiment based upon observation of levels at which whales stop or do not stop clicking in response to naval sounds.

The minimum exposure for controlled exposure experiments should not be much below that at which silencing was first observed if silencing is likely to be one of the first responses. The maximum exposure could be defined empirically as an exposure that animals regularly receive on the range with no known risk of injury or stranding.

Perhaps the most cautious approach to conducting the first CEEs would involve slowly increasing the received level from the minimum value and then ceasing transmission as soon as the animal ceased clicking. If the animal were tagged, the tag would be able to provide much more detail about the precise behavior of the tagged whale after it ceased vocalizing, but there is some risk that if the response were minor and short enough that it would not help define risk factors for stranding.

For example, Aguilar de Soto et al. (2006) happened to observe what appears to be a disturbance reaction of a Cuvier's beaked whale to a loud ship passing overheard. Aguilar de Soto et al. (2006) describe eight foraging dives from a 15.6 hour tag record in the Ligurian Sea (Figure D2). This is a region with heavy shipping traffic, and during the fourth dive of this tagged whale, a ship passed overhead, elevating noise levels by 10-20 dB in the 1-40 kHz third octave bands. The maximum broad-band (356 Hz to 44.8 kHz) level received during the ship passage was 136 dBrms re 1 μPa. Near the time of this exposure, the tagged whale broke off its deep foraging dive and returned to the surface with a normal ascent rate. This dive was 15 min shorter than the other 7 dives, with significantly fewer buzzes (indicating attempts to capture prey; Johnson et al. 2004, Madsen et al. 2005). However, there is little information in this response that would help clarify which of the causal hypotheses about stranding is correct.

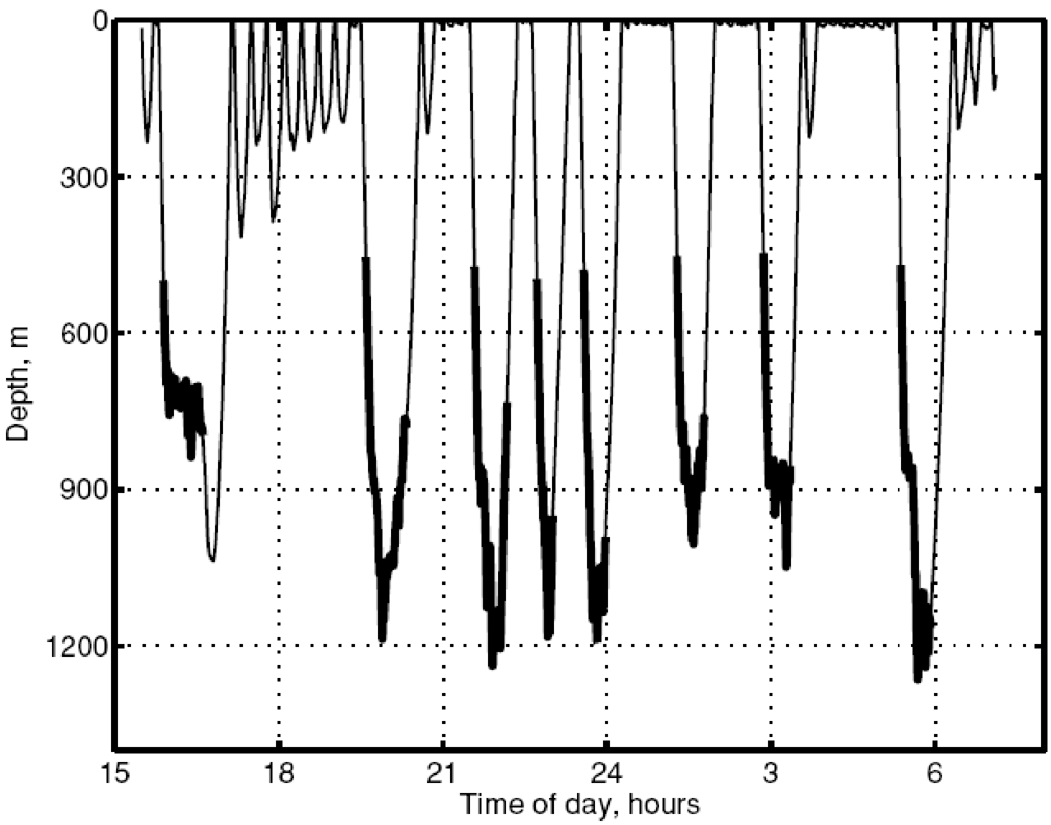


Figure D2. Case study of an observation indicating a response to an uncontrolled exposure to noise. Dive profile of a Cuvier's beaked whale, *Ziphius cavirostris*, tagged in the Ligurian Sea. The fourth dive is shorter than any other deep foraging dive recorded for this species. The whale broke off the dive when noise levels were elevated by a ship passing overhead.

Recent research on pathology of stranded cetaceans raises the hypothesis that some species may be at risk of a decompression-like syndrome even though they are breath-hold divers (Fernandez et al. 2005; Jepson 2003). Some of the animals with the most extreme symptoms include beaked whales stranded during naval sonar exercises. This led a workshop on beaked whale strandings sponsored by the US Marine Mammal Commission to conclude "Whereas no potential

mechanisms were eliminated, one in particular was highlighted as plausible and in need of intensive study to either eliminate or support: gas bubble formation mediated through a behavioural response." (Cox et al. 2006)

The diving behavior of beaked whales does indeed suggest that they are extreme divers. Their foraging dives have the longest average duration and deepest average depth of any diver (Tyack et al. 2006b). Rough calculations suggest that their dives are about twice as long as could be supported by aerobic metabolism, and there are long intervals between foraging dives when beaked whales may be metabolizing the products of anaerobic metabolism or recovering from some other aspects of the dive. If there is insignificant diffusion of gas from air-filled cavities to the circulation deeper than the depth of lung collapse (probably <100m), then there appears to be little risk of supersaturation during the long foraging dives. However, *Mesoplodon* and *Ziphius* ascend from the foraging dives more slowly than other deep diving species. This reduces the time available for foraging, and suggests that there may be some constraint on diving physiology that requires the slow ascent.

Our current understanding of beaked whale diving suggests two potential risk factors for decompression sickness (DCS) injury in response to sonar. The first hypothesis is that beaked whales are supersaturated during foraging dives, and that the slow ascent prevents DCS. If this were true, then rapid ascent in response to sonar might pose a risk. The flaw with this idea is the lack of evidence for supersaturation or a mechanism for increased saturation below the depth of lung collapse. Experimental data demonstrate that dolphins can develop 300% saturation in their muscle after a rapid series of dives to the depth of lung collapse (Ridgway & Howard 1979) and a similar series of shallow dives caused DCS-like symptoms in a human breath-hold diver (Paulev 1965). If beaked whales at the surface responded to sonar by a similar series of shallow dives, this would pose a risk of high saturation levels and possibly DCS. These two hypothesized risk factors would suggest different contexts for CEEs. The rapid ascent hypothesis would suggest starting exposure when the subject is foraging at depth, while the multiple shallow dive hypothesis would suggest starting exposure when the subject is at the surface. If one started exposure while the whale was clicking at depth in order to monitor vocal responses in real time, then if the whale stops responding soon after exposure ceases, as shown in the Aguilar de Soto et al. (2006) case, then in order to test the multiple shallow dive hypothesis, one might need to maintain the exposure long enough for the whale to surface and make one of its shallow recovery dives.

Making decisions about how long to maintain duration of exposure may require deliberation balancing the goal of sorting out which hypothesis about stranding is correct vs being conservative that the animal not be put at risk during the exposure. Since the goal of any beaked whale CEE must be to define safe exposure levels while minimizing risk to the subject, the response used in the CEE should ideally be a safe indicator of an exposure that could pose greater risk if prolonged or increased. It is therefore important to decide before CEEs are conducted whether if there is little indication that silencing is associated with risk during very short exposures, how to proceed to define the indicator response. One important component of this involves an effort to model the risk of increase in bubble size based upon dive profiles in order to make sure that the response is not risky. If risk can develop within a single dive, it may

be necessary to add the capability of telemetering a signal from the tag which is recording the response data during the dive.

The goal of this second phase of studying the effect of sonar on beaked whales should be to define a safe response that can indicate risk to the animal. This is likely to require obtaining sufficient data to identify which causal hypothesis(es) are involved in the risk. This phase need not involve a large sample size if the responses are clear cut and illuminating.

The third phase of studying the effect of sonar on beaked whales would involve defining what exposure is associated with the initiation of the indicator response. This will require a larger sample size, sufficient to estimate the dose:response curve. The more variable the dosage required to elicit the response, the larger the required sample size, especially if there is systematic variability as a function of age/sex class, behavioral context etc. If mitigation may involve alternate stimuli, or if there are questions about differential responsiveness to different stimuli, design of a full CEE research program with beaked whales might involve stimuli other than the mid-frequency sonar signals associated with strandings. There is growing concern about the effects of sounds other than mid-frequency naval sonars on beaked whales. For example, responses of beaked whales to low frequency sonars such as SURTASS LFA need to be tested. Several strandings of beaked whales have been tentatively linked to operation of airgun arrays used for geophysical surveys. There is one report that a stranding of two *Ziphius* occurred in the Gulf of California when a seismic vessel was operating tens of km away (Malakoff 2002), and another report of a mass stranding of beaked whales concurrent with seismic survey, but at a range of hundreds of km (Gentry 2002). While the evidence for such a link is weak, this suggests a need to test responses of beaked whales to airguns. Finally, there has been interest in designing mid-frequency sonar signals that retain ASW functionality while posing less of a risk to beaked whales. The effectiveness of any such signals would need to be tested. Adding several different signals to the playback design for each tagged subject can increase experimental controls which improves the power of the experiment (Nowacek et al. 2004), but would require increased attachment durations of the tag the more stimuli in order to guarantee sufficient pre- and post-exposure control data for each exposure.

Figure D3 illustrates an example of how one might structure a multi-stimulus controlled exposure to a tagged whale. This example would collect several dives of pre- and post-exposure data, but would assume that the animal has reset to a baseline behavioral state once it starts a foraging dive again. Depending upon what the duration and quality of response is observed in phase II, this assumption may or may not be accurate. Any increased duration between exposures would increase the duration of tag attachment required for successful experiments. One cannot prevent tags from occasionally coming off prematurely, but (Nowacek et al. 2004) found that this could be incorporated into the experimental design.

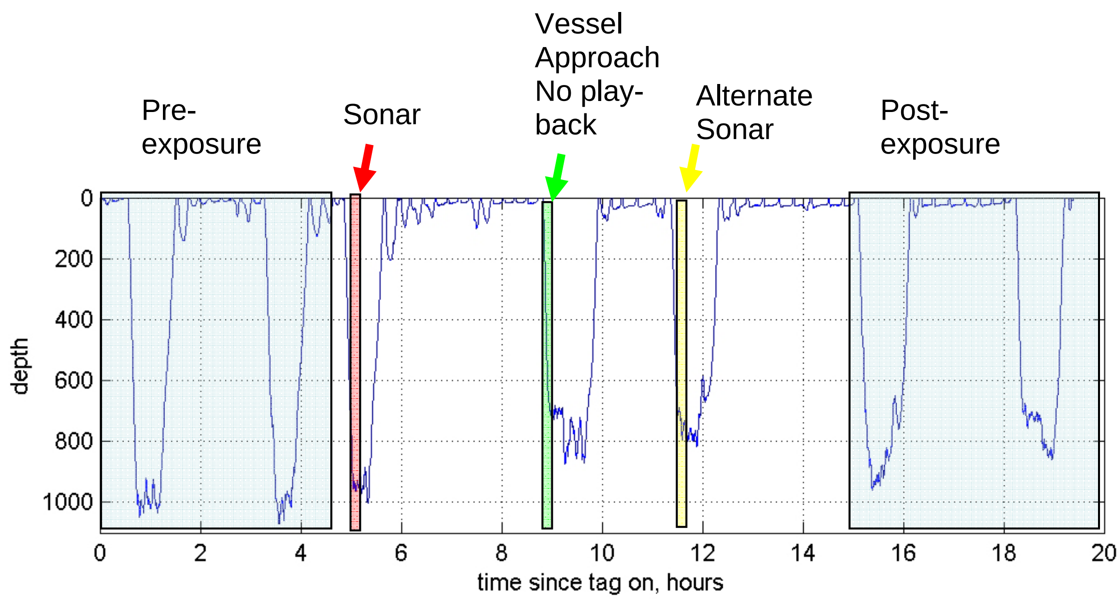


Figure D3. Example of possible transmission protocol for a multi-stimulus test overlaid on a 19.5 hour dive record from a *Mesoplodon densirostris* tagged on the AUTEC range.

For the overall minimization of risk to beaked whales from anthropogenic sounds, testing responses to these other signals may be just as important as mid-frequency sonar signals. If alternate stimuli pose much less of a risk, then establishing differential response may be more important than extensive quantification of dose:response for the signal that is known to pose a risk. Either way, it will be critical to extend this work beyond the AUTEC range where the whales may be habituated to sonar signals, which are commonly transmitted on the range. Such work will require development of a passive acoustic monitoring capability that can be deployed away from Navy ranges. Such monitoring may also become an important part of mitigation strategies. At AUTEC where whales are regularly exposed to sounds of naval activities, there is reduced concern about conducting a series of low intensity experiments, even if later subjects may have detected faint sounds of earlier experiments, as the experimental exposures would be insignificant compared to ongoing sound exposure. But establishing a design to work with naïve animals will require that each subject has not heard previous experiments, or uncontrolled habituation may contaminate the results. Indeed this was a problem with the (Nowacek et al. 2004) results where the last subject was the only one not to respond to the alert stimulus. It is impossible to distinguish whether this individual was less sensitive than the others tested, or whether it had habituated after hearing some of the previous five experiments where neither its exposure nor responses were measured. For this reason, it either will be necessary to develop several field sites, or to consider operating from a ship that can find whales, deploy an array that can localize them in real time, conduct the experiment, and then move on.

Once work with tagged whales has defined detailed responses of habituated and naïve whales to sonar signals, and has provided preliminary dose:response data, there is still likely to be a need for designing a monitoring capability that can make sure that these data used for risk management are appropriate for other contexts, other sites, and other populations. If the earlier phases make it possible to define a vocal response as an indicator of risk, then such monitoring

could be accomplished using passive acoustic monitoring, which is particularly well suited to monitoring for effects over long spatial and temporal scales. If detailed data from a device like a tag are required, then extending the time scale will require extending the tag duration. A variety of different techniques are used to attach tags for durations of hours to months and even years in the case of species such as sperm whales. Remote data telemetry would probably be required for longer duration tags, and since the amount of data that can be transmitted is limited and requires power, this argues for considerable signal processing and data analysis on the tag. Either way, one important outcome of the short term studies could be the development of validated capabilities to monitor the effects of operational exercises over the duration of the exercise and beyond.

Sequence of stages for CEE program
There are four logical stages to study the effects of naval sounds on beaked whales.

Stage 1: Measure changes in vocal behavior of beaked whales on the AUTEC range as a function of exposure. This can be used to establish the range of exposures to be planned for stage 2

Stage 2: The first stimulus to use in controlled exposures is short exposures at low levels of the sounds of sonars that actually have been involved in strandings. The key here is to use the sound most likely to trigger a response, but in an exposure least likely to pose a risk to the subject. Most studies of responses of marine mammals to sound demonstrate responses soon after the start of exposure, and there are almost no reports of responses lasting much beyond the exposure duration. Therefore, this experiment is designed to detect the onset of a response that if prolonged could be risky, but to cease the response before it poses a risk. This work would not require an actual naval vessel but could be conducted from a vessel deploying an underwater sound source. The protocol would involve finding whales using passive acoustic monitoring, tagging one, collecting pre-exposure data, and then transmitting the sound. The behavior of the whale would be monitored in real time so transmission could cease as soon as a response is observed, or as soon as a response is diagnostic.

Stage 3
Titrating exposure required to elicit indicator response from different stimuli: If a diagnostic but safe response is detected using the short, low level exposure in stage 2, then the next step would be to test what exposures are required to elicit the response from a variety of signal types, including 53-C type signals, LFA signals, and airgun sounds. In order to test for differential responsiveness to these signals, the most powerful experimental design would compare responses of the same individual to several of these signals in the same behavioral context, with order of presentation randomized between individuals. The time required to achieve this will depend upon the time required for animals to return to baseline. Phase 2 should provide some initial indication of this time. If the subjects are less responsive to some stimuli, this would both provide critical insight for mitigation measures, and would strengthen the experimental design.

Stage 4. Development and validation of long term monitoring for effects. One important outcome of the previous three phases should be the development of validated capabilities to monitor the effects of operational exercises over the duration of the exercise and beyond.

Literature Cited for Appendix D

Aguilar Soto, N., M. Johnson, P. T. Madsen, P. L. Tyack, A. Bocconcelli, and J. F. Borsani. 2006. Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? *Marine Mammal Science* **22**, 690-699.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. & Benner, L. 2006. Why Beaked Whales? Report of Workshop to Understand the Impacts of Anthropogenic Sound. *Journal of Cetacean Research and Management*, 7(3):177-187.

Fernandez, A., Edwards, J. F., Rodriguez, F., Monteros, A. E. d. l., Herraez, P., Castro, P., Jaber, J. R., Martin, V. & Arbelo, M. 2005 ''Gas and Fat Embolic Syndrome'' Involving a Mass Stranding of Beaked Whales (Family Ziphiidae) Exposed to Anthropogenic Sonar Signals. *Veterinary Pathology* **42**, 446–457.

Gentry, R. L. 2002. Mass stranding of beaked whales in the Galapagos Islands, April 2000. National Marine Fisheries Service, Silver Spring.

Harwood, J. 2000 Risk assessment and decision analysis in conservation. Biological Conservation 95: 219-226.

Jepson, P. D. 2003 Whales, sonar and decompression sickness. *Nature* **425**, 575-576.

Johnson, M. P., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N. & Tyack, P. L. 2004 Beaked whales echolocate on prey. *Proceedings of the Royal Society of London, B* **271**, S383-S386.

Madsen, P. T., Johnson, M., Aguilar de Soto, N., Zimmer, W. M. X. & Tyack, P. L. 2005 Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*). *The Journal of Experimental Biology* **208**, 181-194.

Madsen P.T., Johnson M., Miller P., Aguilar de Soto N. and Tyack P. 2006. Quantitative measures of airgun pulses impinging on sperm whales using onboard tags and controlled exposures. *Journal of Acoustical Society of America* **120**:2366-2379.

Malakoff, D. 2002. Seismology - Suit ties whale deaths to research cruise. Science 298(5594): 722-723.

Malme, C. I., Miles, P. R., Tyack, D. P. L., Clark, C. W. & Bird, J. E. 1985 Investigation of the potential effects of underwater noise from petroleum industry activities on feeding humpback whale behavior. Cambridge MA: BBN Laboratories Inc.

Nowacek, D. P., Johnson, M. P. & Tyack, P. L. 2004 North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. *Proceedings of the Royal Society of London, B* **271**, 227-231.

Paulev, P. 1965 Decompression sickness following repeated breath-hold dives. *Journal of Applied Physiology* **20**, 1028-1031.

Ridgway, S. H. & Howard, R. 1979 Dolphin Lung Collapse and Intramuscular Circulation During Free Diving: Evidence from Nitrogen Washout. *Science* **206**, 1182-1183.

Tyack, P. L., Gordon, J. & Thompson, D. 2004 Controlled Exposure Experiments to Determine the Effects of Noise on Marine Mammals. *Marine Technology Society Journal* **37**, 41-53.

Tyack, P. L., Johnson, M. P., Aguilar de Soto N., Madsen, P. T. 2006a Acoustic behavior of beaked whales, with implications for acoustic monitoring. Proceedings of the IEEE Oceans06 Conference.

Tyack, P. L., Johnson, M., Soto, N. A. d., Sturlese, A. & Madsen, P. T. 2006b Extreme diving behaviour of beaked whale species known to strand in conjunction with use of military sonars. *Journal of Experimental Biology*. **209**, 4238-4253

Wartzok, D., Altmann, J., Au, W., Ralls, K., Starfield, A. & Tyack, P. L. 2005 *Marine Mammal Populations and Ocean Noise: Determining when noise causes biologically significant effects.* Washington, D.C.: National Academy Press.

Appendix E. How to determine the relevant response parameters and safe doses for Controlled Exposure Experiments.

Peter Tyack
Biology Deparment
WHOI

While there are enough cases when atypical mass strandings of beaked whales coincide with a mid-frequency naval sonar exercise to suggest a link between sonar exposure and stranding, the causal chain of events leading from exposure to stranding is unknown. This poses problems for selecting response parameters and estimating safe doses for controlled exposure.

Determination of relevant response parameters
The basic principal for selecting response parameters in experimental science is to select parameters that are relevant to test specific hypotheses. Several papers and workshops have reviewed the hypotheses that have been suggested for the cause of strandings that coincide with sonar exposure. Many of these hypotheses were discussed in a series of workshops from 2004-2006. A workshop was convened by the US Marine Mammal Commission from 13-16 April 2004 in Baltimore MD, entitled “Beaked whale technical workshop.” Another workshop was convened at the annual conference of the European Cetacean Society held in La Rochelle France on 3 April 2005. This workshop was entitled “Research priorities to reduce risk to beaked whales from military sonar.” Another workshop was convened by the NATO Undersea Research Center in Lerici, Italy from 2-5 May 2005 on “Effects of Sound in the Ocean on Marine Mammals”. The best summary of hypotheses stemming from these meetings is in Cox et al. (2006), with the exception that this paper did not include a hypothesis presented in Lerici by Steven Cole of the Australian Royal Navy. Cole pointed out that most of these strandings occurred in areas with relatively warm seawater, and he proposed a hyperthermia hypothesis: that panicking whales might overheat, and this could cause physiological problems. All of these hypotheses, including the hyperthermia hypothesis of Cole, are listed in Table E1.

Table E1. List of hypotheses concerning the causes of strandings of beaked whales coincident with sonar exercises.

Hypothesis	Sub-hypothesis	Test	Consequences for Mitigation
1. Behavioral response leads directly to stranding with no injuries other than those induced by stranding.	Panicked flight	CEE of sonar signals Observation of whales near sonar exercises	Limit risk of injury by operating sonar farther from coast than flight distance
	Anti-predator response	CEE of killer whale and sonar signals	Likely initiated at detection threshold May be possible to habituate
2. Behavioral response leads to potentially lethal injury independent of stranding; injured	DCS syndrome	Model N2 saturation and bubble formation Sensor on tag for bubbles in blood or tissue (may use	Response may need to have extended duration for risk of injury Risk of injury far from coast if DCS does not

animals may strand and develop further injuries		surrogate species) Measure behavioral (and physiological if possible) response to sonar signals	require shallow water
	Hyperthermia	Heat flux sensor on tag Measure response to sonar signals	Risk may be less the cooler the water temp than body temp
3. Sound directly causes injury, followed by behavioral response leading to stranding	Acoustically mediated bubble growth	Measure or model saturation levels from dive profiles Lab tests with fresh tissue and blood	Requires close range to ship May be able to mitigate by detecting whales within range
	Hemorrhagic diathesis	Test blood for clotting factors Necropsy protocol	Injury relates to stress – usually high level of sound required to trigger acute stress response
	Tissue shear/acoustic resonance	Necropsy protocol Experimental tests with fresh stranded animals	Requires close range to ship May be able to mitigate by detecting whales within range

The first set of hypotheses proposes that a behavioral response may lead to stranding, either simply as panicked flight, or as part of an anti-predator response. Since this kind of behavior is quite context specific, these hypotheses should be tested with an unbiased sample of wild animals at sea. The locations of the animals should be tracked with sufficient precision to estimate their velocity, and it would be extremely useful to measure precise parameters of locomotion such as fluke rate. For most deep diving species such as beaked whales, it is very difficult to measure these parameters using visual observation. The DTAGs developed at WHOI not only can measure acoustic exposure, but also provide a three-dimensional track of the movements of the tagged animal along with the ability to measure fluke rate from fluctuations in the pitch angle (Johnson and Tyack 2003).

The second set of hypotheses posit that exposure to sound may trigger a behavioral response that leads to adverse physiological consequences, either a decompression-like syndrome or hyperthermia. As with the first set of hypotheses, since the initial link in the causal chain involves a behavioral response, which may be context specific, studying the behavioral component of these hypotheses should involve work with an unbiased sample of animals in the wild. Hyperthermia in warm water would be likely to lead to an elevation of the skin temperature of the animal, along with a relatively high heat flux. Instruments do exist to measure surface temperature of an animal remotely in air, and it might be possible to use this when a marine mammal surfaces, but tagging is probably a more reliable way to measure these parameters. A thermistor can easily measure temperature at the surface of the skin, and heat flux sensors have been used successfully on marine mammal tags (Pabst et al. 2002; Willis and Horning 2005). Some of the more physiological issues relating to risk of bubble growth from specific dive profiles and obtaining some of the anatomical and physiological parameters required to model decompression are likely to require work with stranded or captive animals.

The third set of hypotheses involves effects that sound may have directly on tissue. There is no plan to expose animals in the wild to sound that could cause injury directly. Rather these kinds of phenomena are best studied using tissue samples from dead animals combined with modeling.

Determination of safe doses for controlled exposure experiments

Controlled exposure experiments to define dose:response relations with beaked whales and sonar sounds must find a safe response indicative of potential risk for stranding following more intense exposure. The goal is analogous to using temporary threshold shift, a harmless effect, as a signpost for studying risk of injury. Defining this indicator response is particularly difficult as the causal chain of events leading to stranding is not known. Thus the initial goal of CEEs in this case should be to find a safe indicator response that also helps narrow the range of hypotheses about the cause of these strandings. For several cases of strandings coincident with sonar exercises (D'Amico 1998; Evans and England 2001), it is known where the ships were when transmitting. However, it is not known where the whales were, which makes it impossible to establish safe exposure criteria based on the strandings themselves.

However, recent work with tagged whales and monitoring the sounds of whales on a navy range suggest an approach for setting the minimum and maximum exposures for initial controlled exposure experiments. The NUWC Marine Mammal Monitoring team has developed software to detect beaked whale clicks on each hydrophone at the AUTEC Navy underwater range and to locate clicks recorded on more than one phone. The range monitoring system can track any acoustic signals within its band, so it can detect and locate anthropogenic sounds such as pingers while it is also tracking whales. As soon as the sensors on the AUTEC range are recalibrated, it should be possible to estimate the received level of anthropogenic sound at each group of beaked whales.

During collaborative field efforts with WHOI and NUWC, the location and duration of periods of clicking was tallied during deep foraging dives of beaked whales. Systematic efforts of this sort during naval operations and during quiet control periods should allow testing of the received levels at which beaked whales move away and/or stop clicking. By associating the movements of whales between and during dives, and the vocal intervals, it should be possible to assess what received levels of exposure to naval sounds may be associated with a change in these behaviors. Since CEEs with tagged animals would be designed to provide more detail about exactly how these animals responded, the received levels at which these responses were initially seen would provide a reasonable goal exposure level for initial CEEs.

There also are naval sonar exercises at the range that use sonars of the sort associated with strandings. Even if whales are present on the range, there are no reports of strandings associated with these exercises. As long as there is no indication of risk to the animals, estimating the acoustic exposure during exercises of beaked whales may be used to establish an initial safe upper limit for exposures on the same range. The more data monitoring for beaked whales before, during, and after such exercises, the better the evidence for lack of risk. Work in areas where the animals are naïve, would probably require a different limit.

Literature Cited for Appendix E.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. & Benner, L. 2006. Why Beaked Whales? Report of Workshop to Understand the Impacts of Anthropogenic Sound. *Journal of Cetacean Research and Management* **7**, 177-187.

D'Amico, A. 1998 Summary Record SACLANTCEN Bioacoustics Panel. La Spezia, Italy, 15-17 June: SACLANT Undersea Research Centre.

Evans, D. L. & England, G. R. 2001 Joint Interim Report, Bahamas Marine Mammal Stranding, Event of 15-16 March 2000, pp. 59: U.S. Department of Commerce and Secretary of the Navy.

Johnson, M. P. & Tyack, P. L. 2003. A Digital Acoustic Recording Tag for Measuring the Response of Wild Marine Mammals to Sound. *IEEE Journal of Oceanic Engineering* **28**, 3-12.

Pabst D. A., McLellan, W. A., Meagher E. M. Westgate A. J. 2002. Measuring Temperatures And Heat Flux From Dolphins In The Eastern Tropical Pacific: Is Thermal Stress Associated With Chase And Capture In The ETP-Tuna Purse Seine Fishery? National Marine Fisheries Service, NOAA, ADMINISTRATIVE REPORT LJ-02-34C

Willis, K., Horning M. 2005. A novel approach to measuring heat flux in swimming animals. Journal of Experimental Marine Biology and Ecology 315, 147–162